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(54) **CHARGE PUMP BASED OVER-SAMPLING WITH UNIFORM STEP SIZE FOR CURRENT DETECTION**

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G11C 11/34 (2006.01)
H02M 3/07 (2006.01)
G11C 16/10 (2006.01)

(52) **U.S. Cl.**
CPC **H02M 3/07** (2013.01); **G11C 16/10** (2013.01)

(58) **Field of Classification Search**
CPC H02M 3/07; G11C 16/10
USPC 365/185.18, 210.11, 226
See application file for complete search history.

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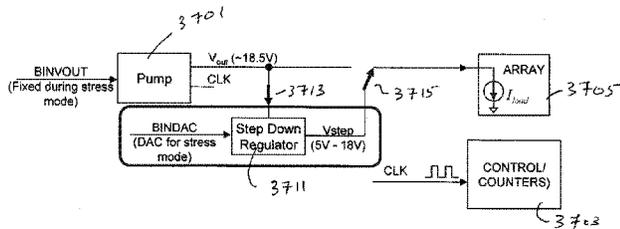
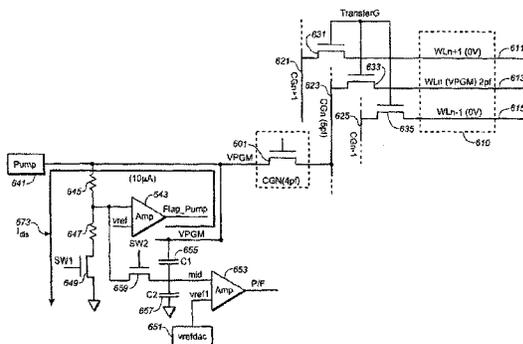
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Primary Examiner — Fernando Hidalgo

(57) **ABSTRACT**

Techniques are presented for determining current levels based on the behavior of a charge pump system while driving a load under regulation. Rather than diving the load directly, a fixed pump output voltage is used to supply a step-down regulator, which it turn drives the load at the selected voltage. While driving the load under regulation, the number of pump clocks during a set interval is counted. This can be compared to a reference that can be obtained, for example, from the numbers of cycles needed to drive a known load current over an interval of the duration. By comparing the counts, the amount of current being drawn by the load can be determined. This technique can be applied to determining leakage from circuit elements, such as word lines in a non-volatile memory.

21 Claims, 31 Drawing Sheets



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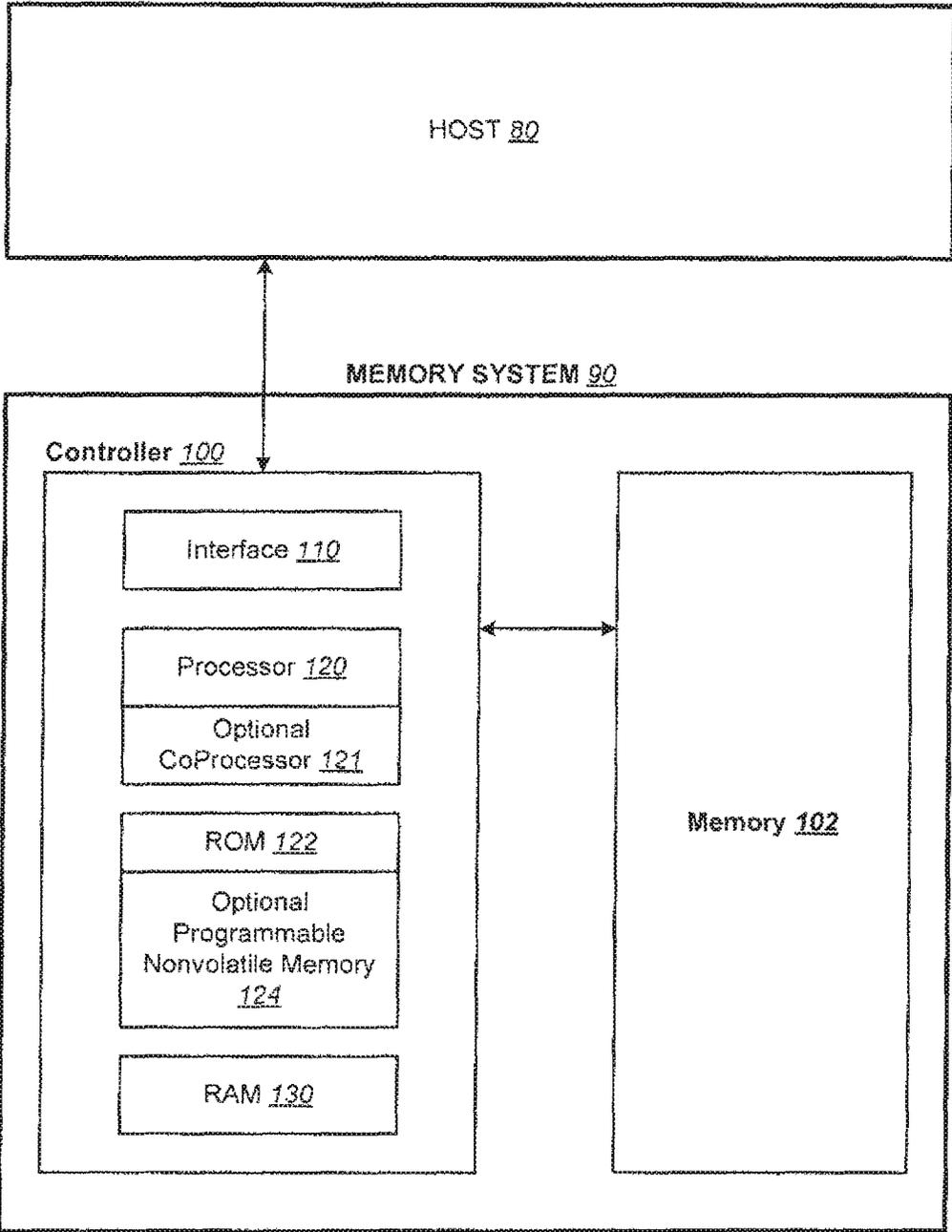


FIG. 1

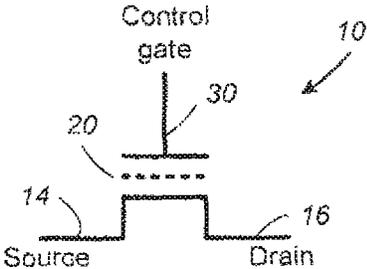


FIG. 2

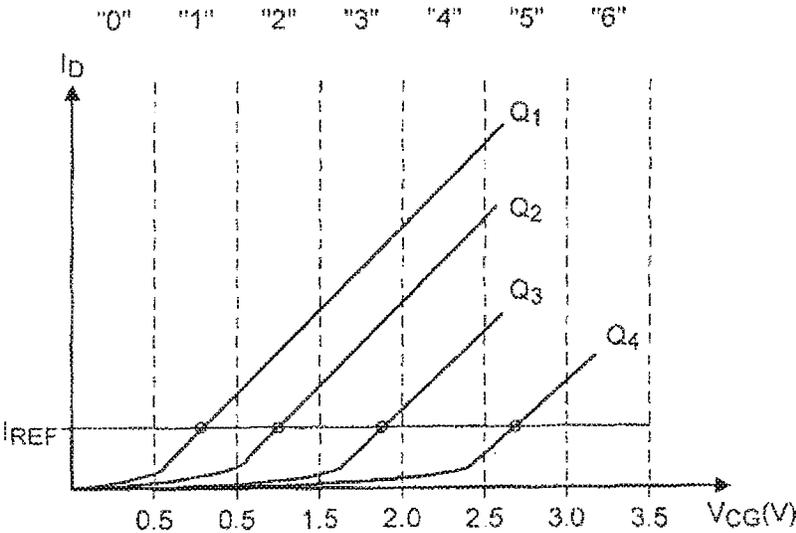


FIG. 3

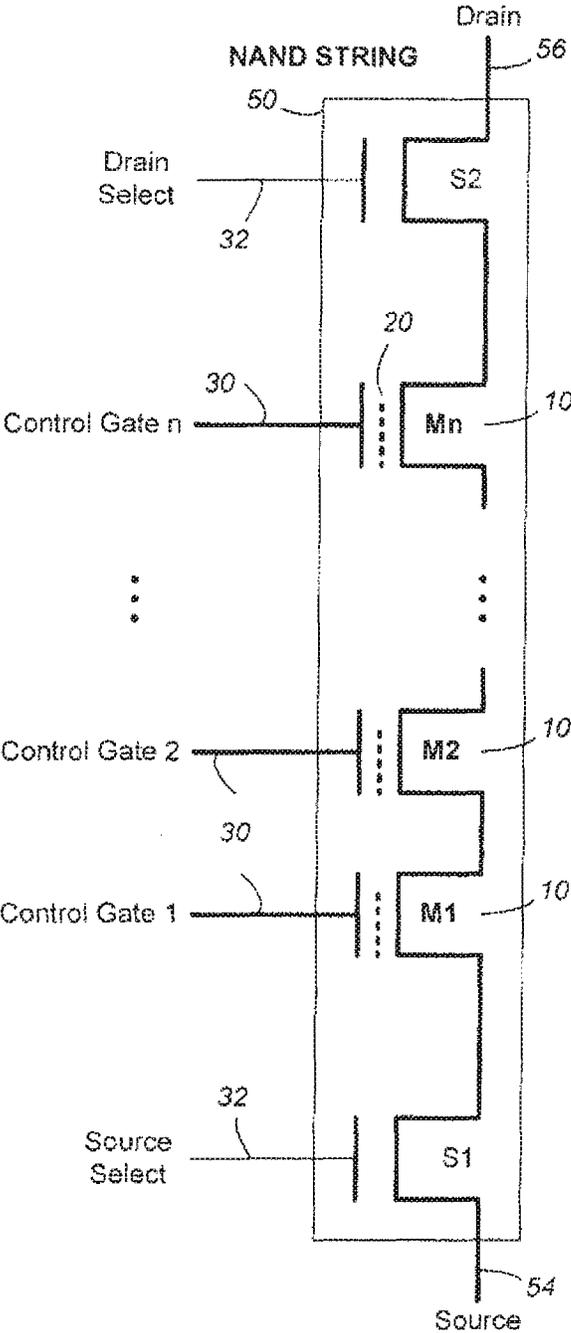


FIG. 4

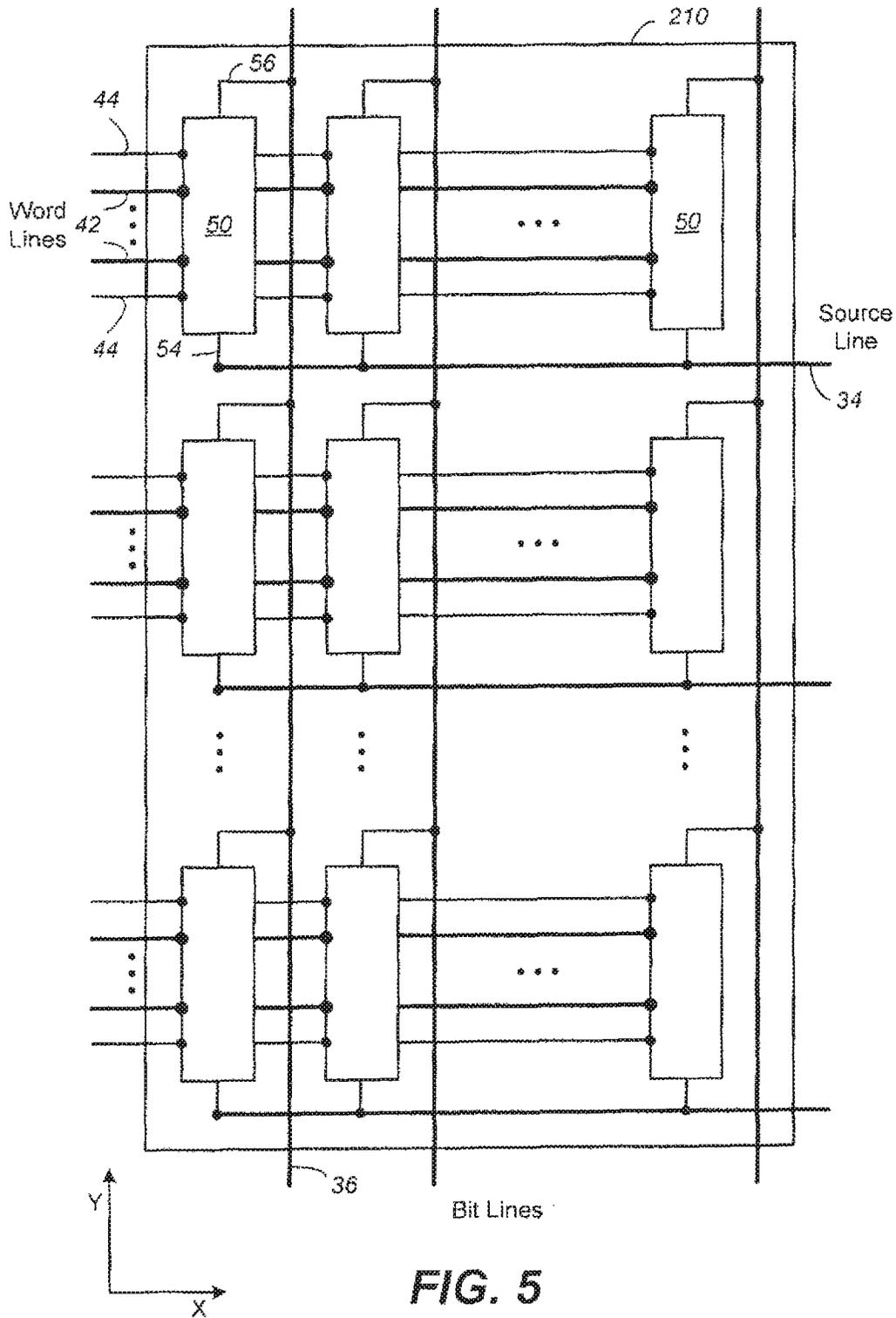


FIG. 5

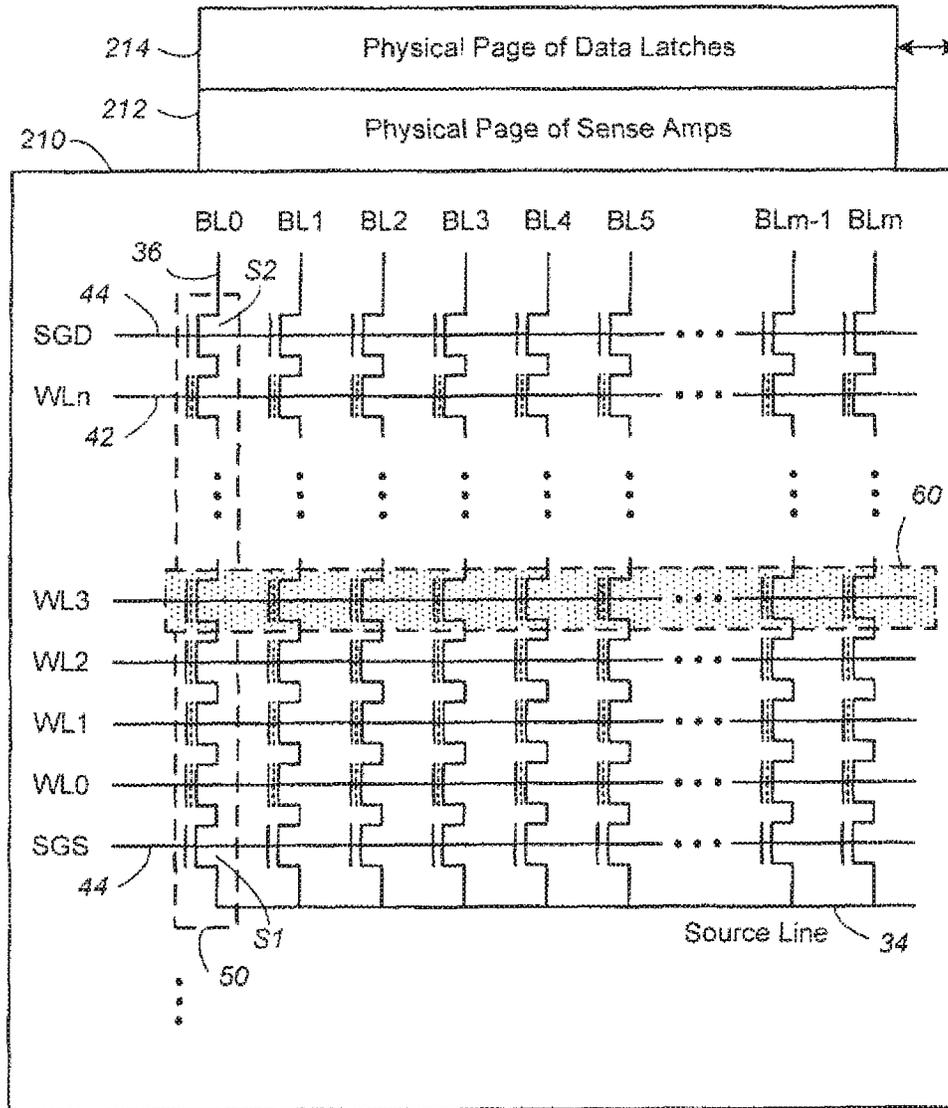
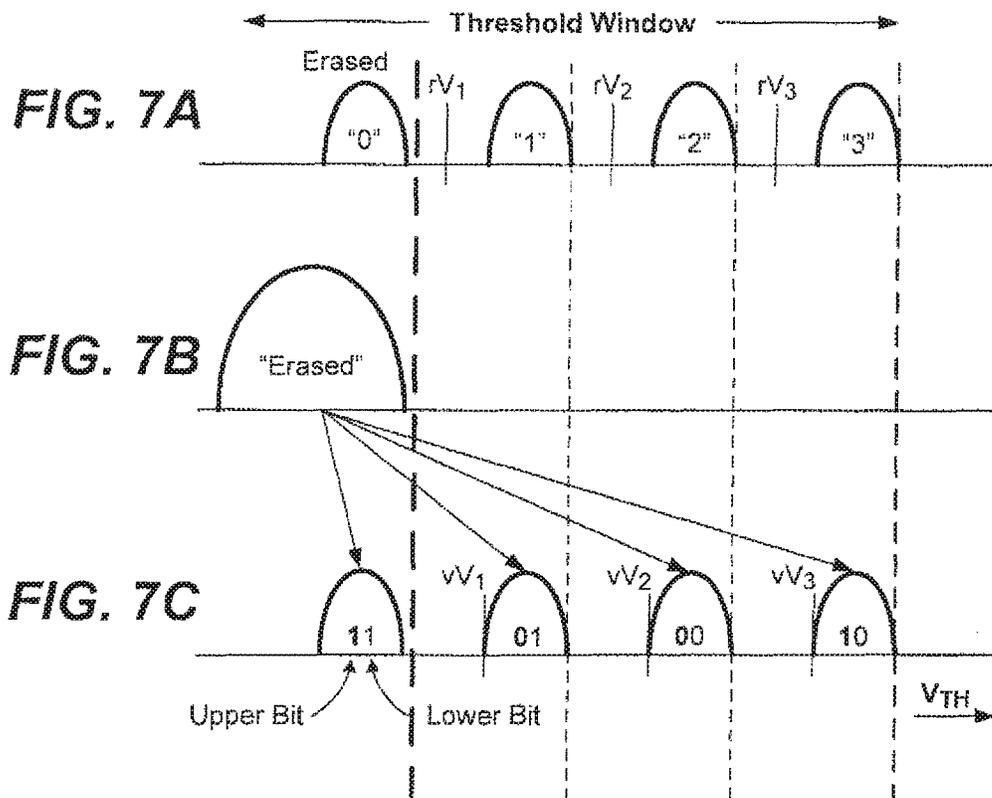


FIG. 6



Programming into four states represented by a 2-bit code

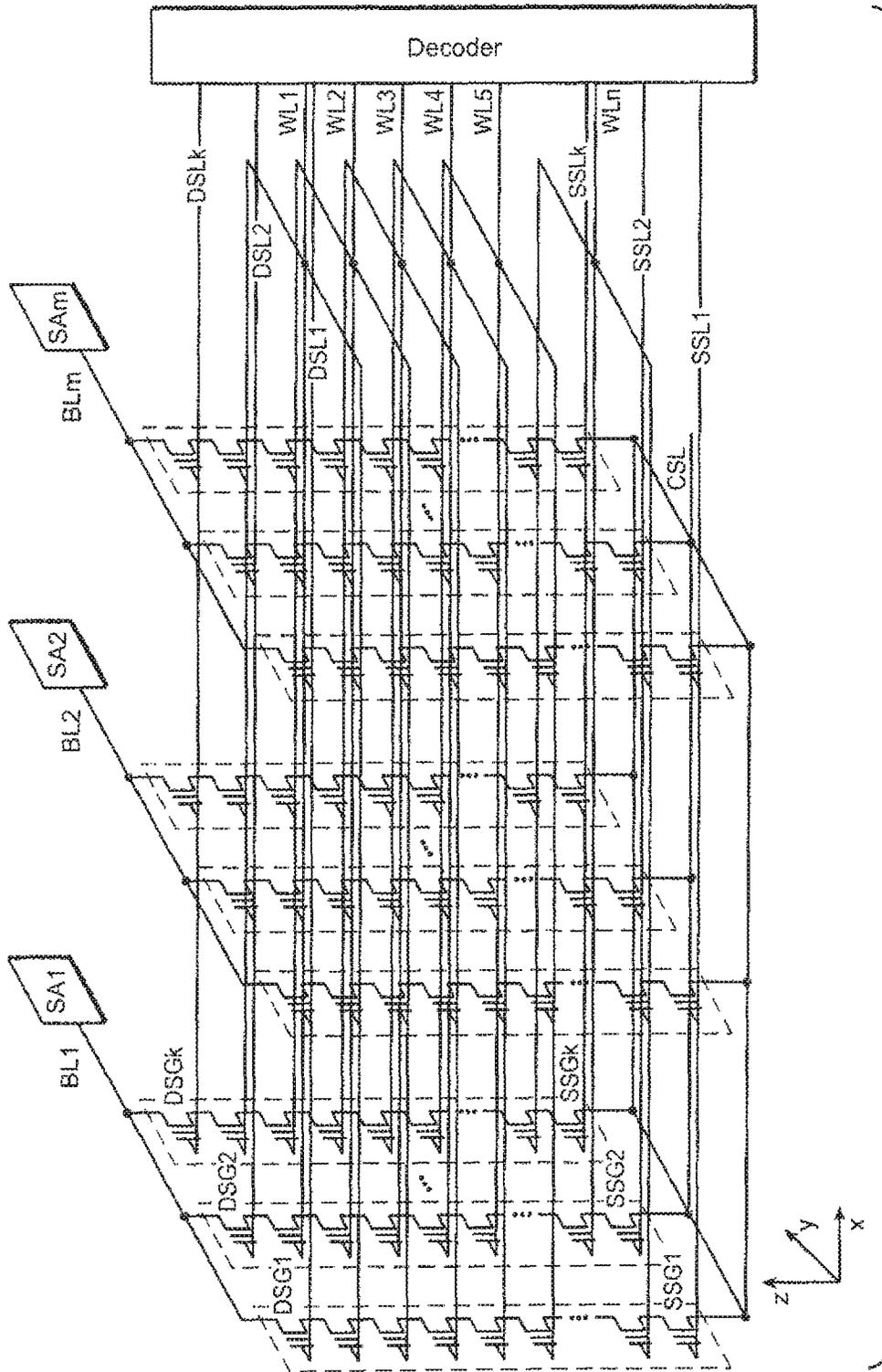


FIG. 8

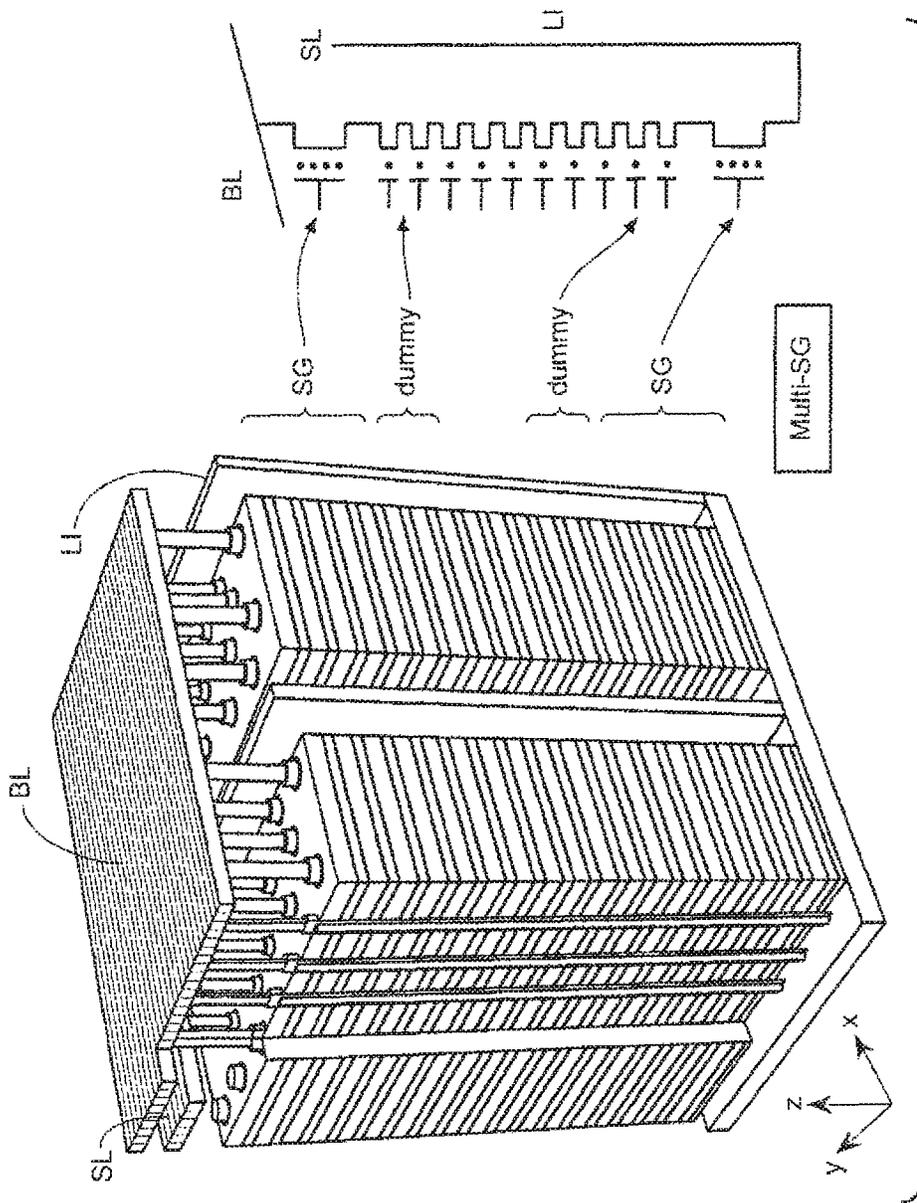


FIG. 9

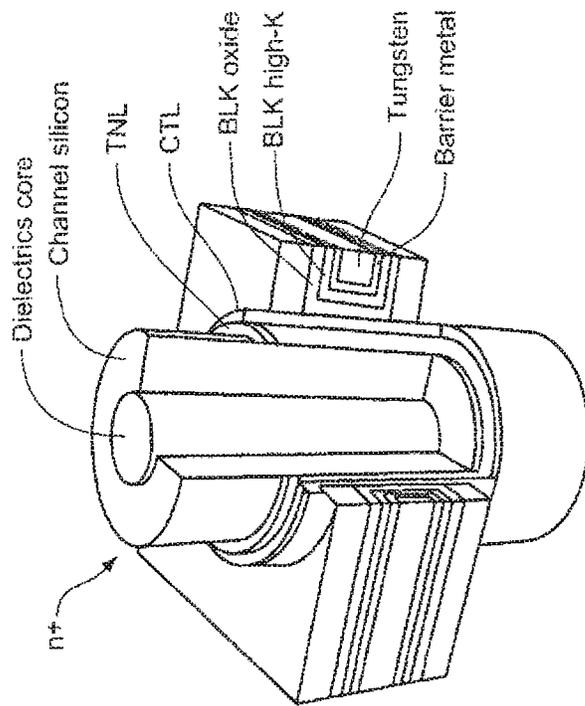


FIG. 12

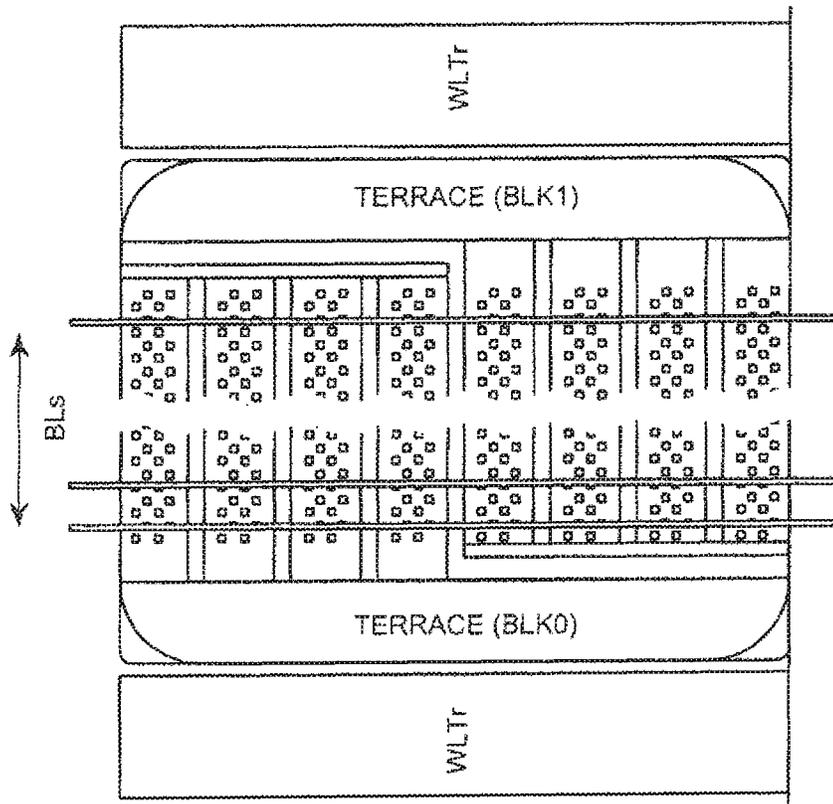


FIG. 10

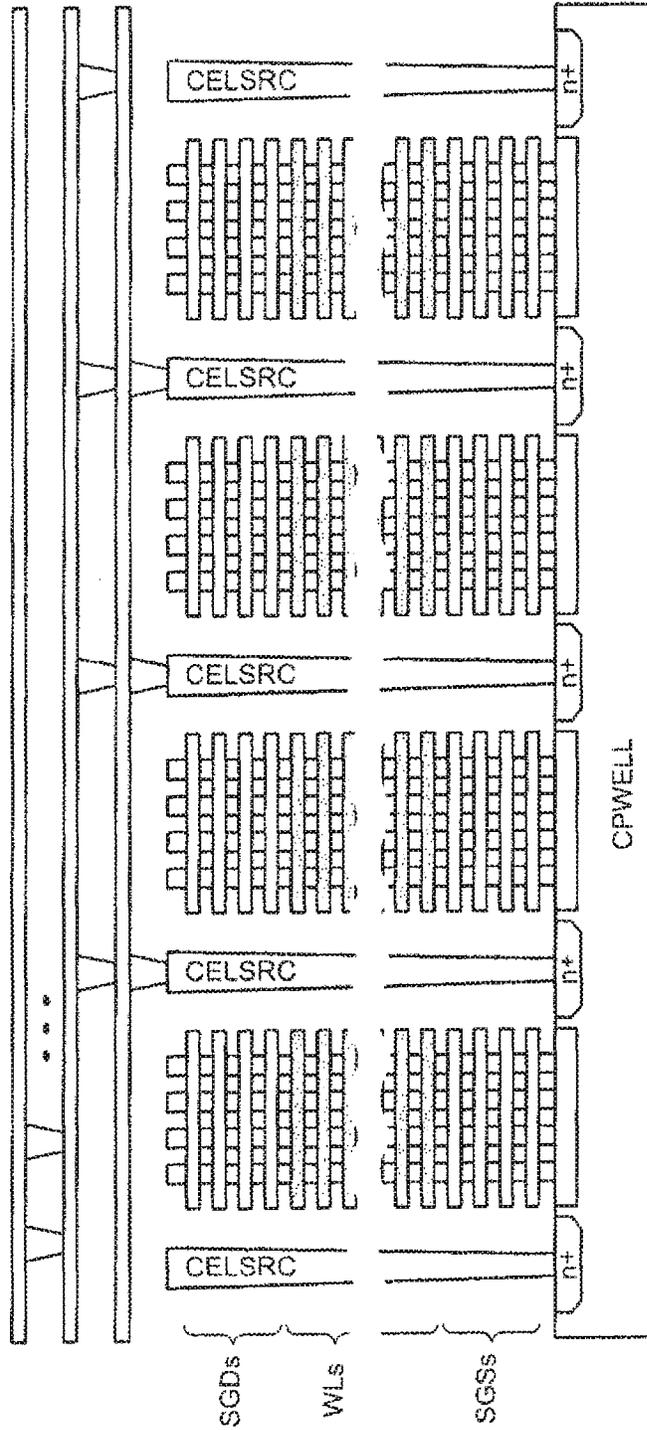


FIG. 11

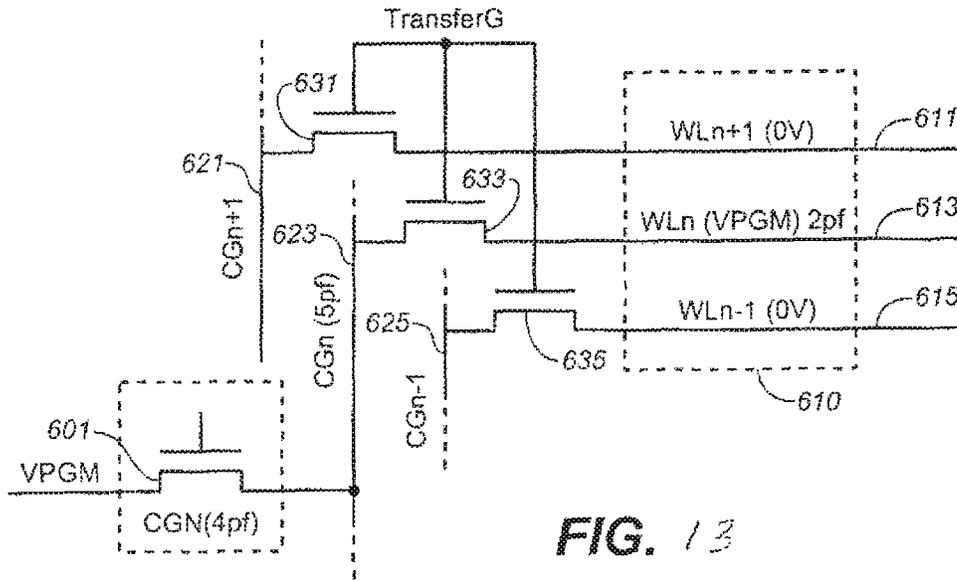


FIG. 13

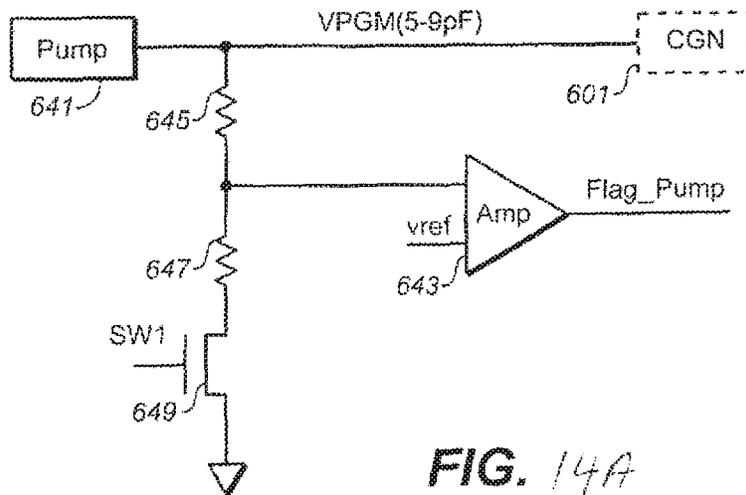


FIG. 14A

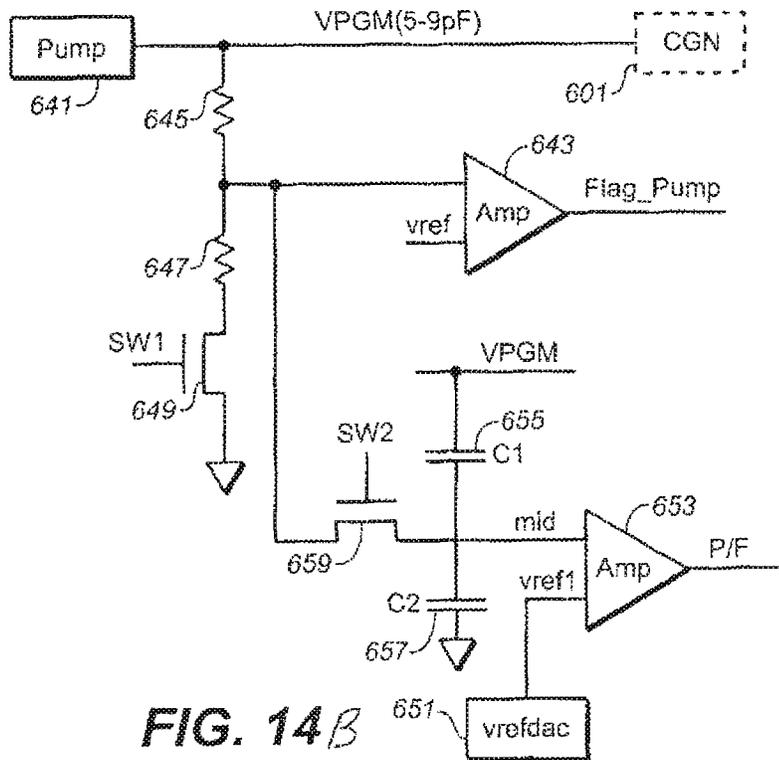


FIG. 14B

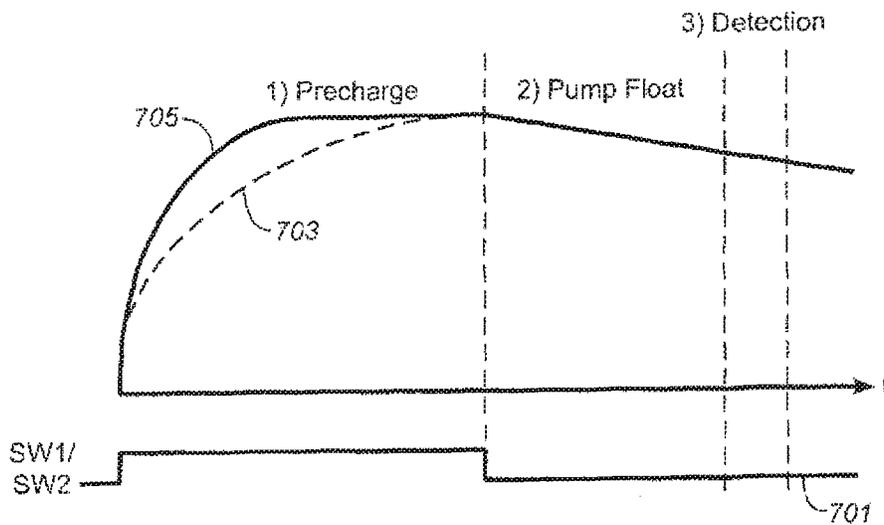


FIG. 15

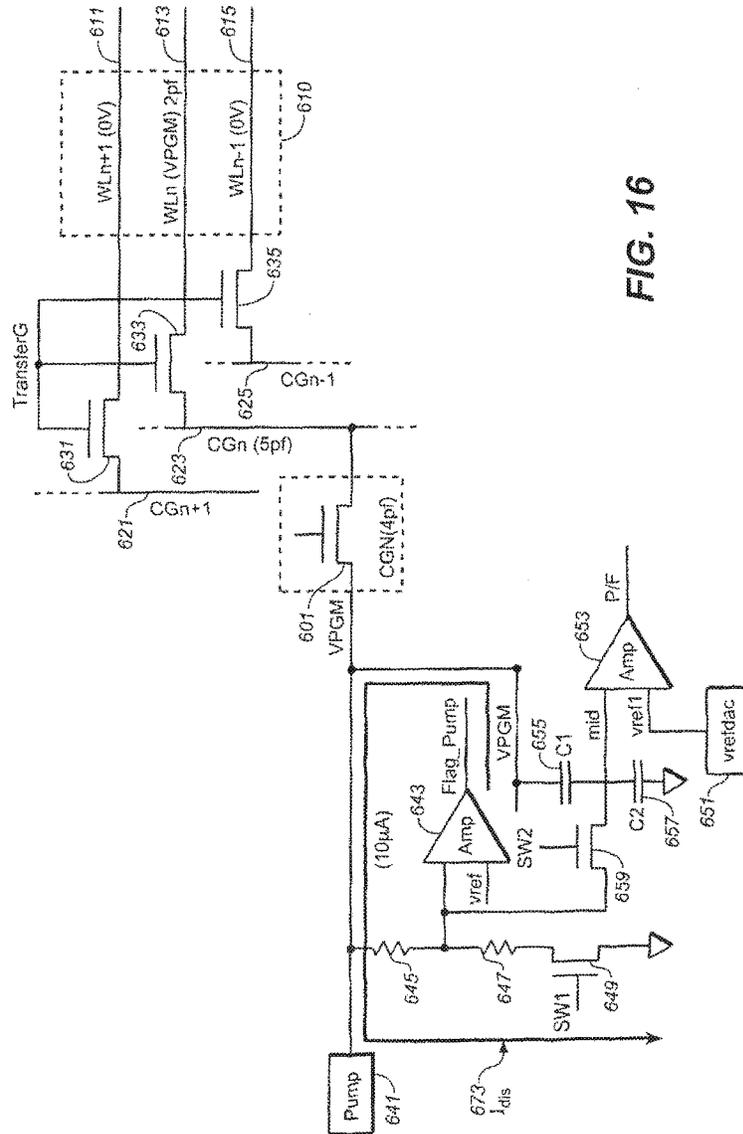


FIG. 16

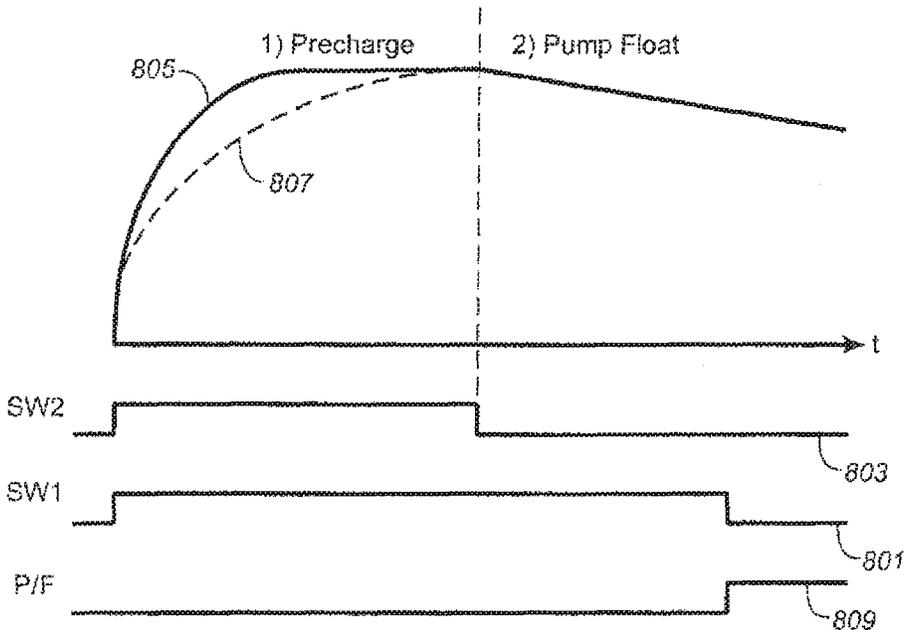


FIG. 17

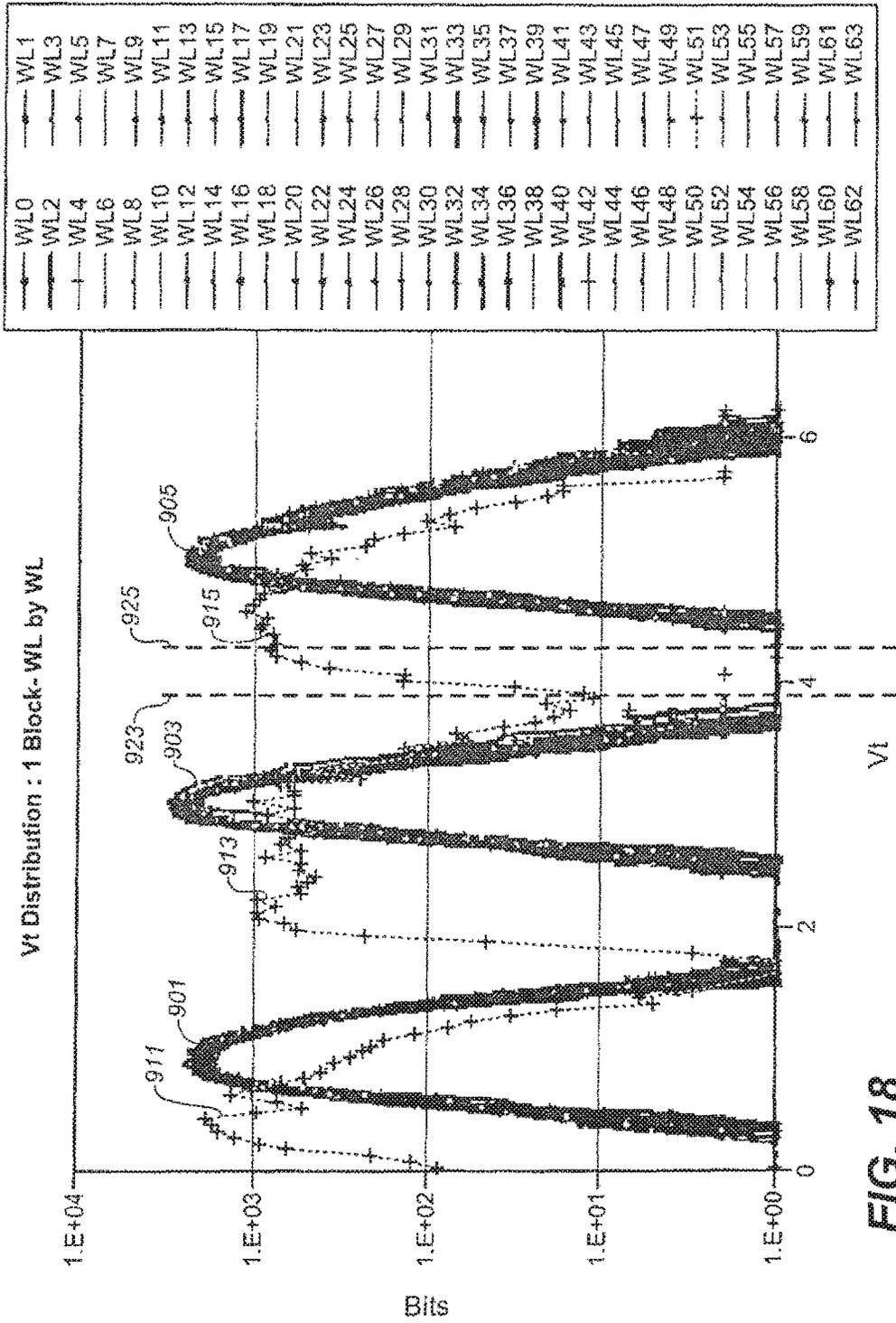


FIG. 18

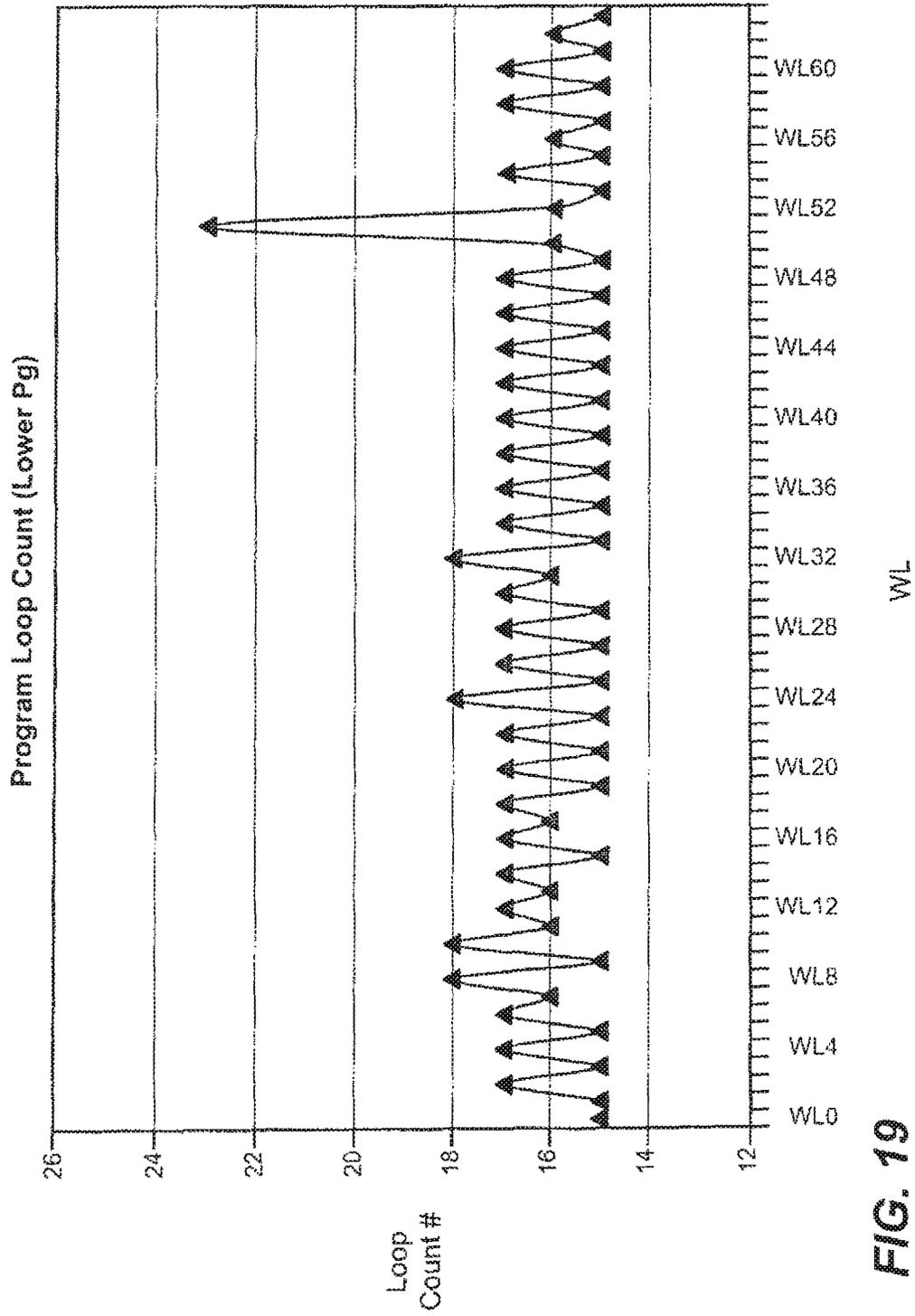


FIG. 19

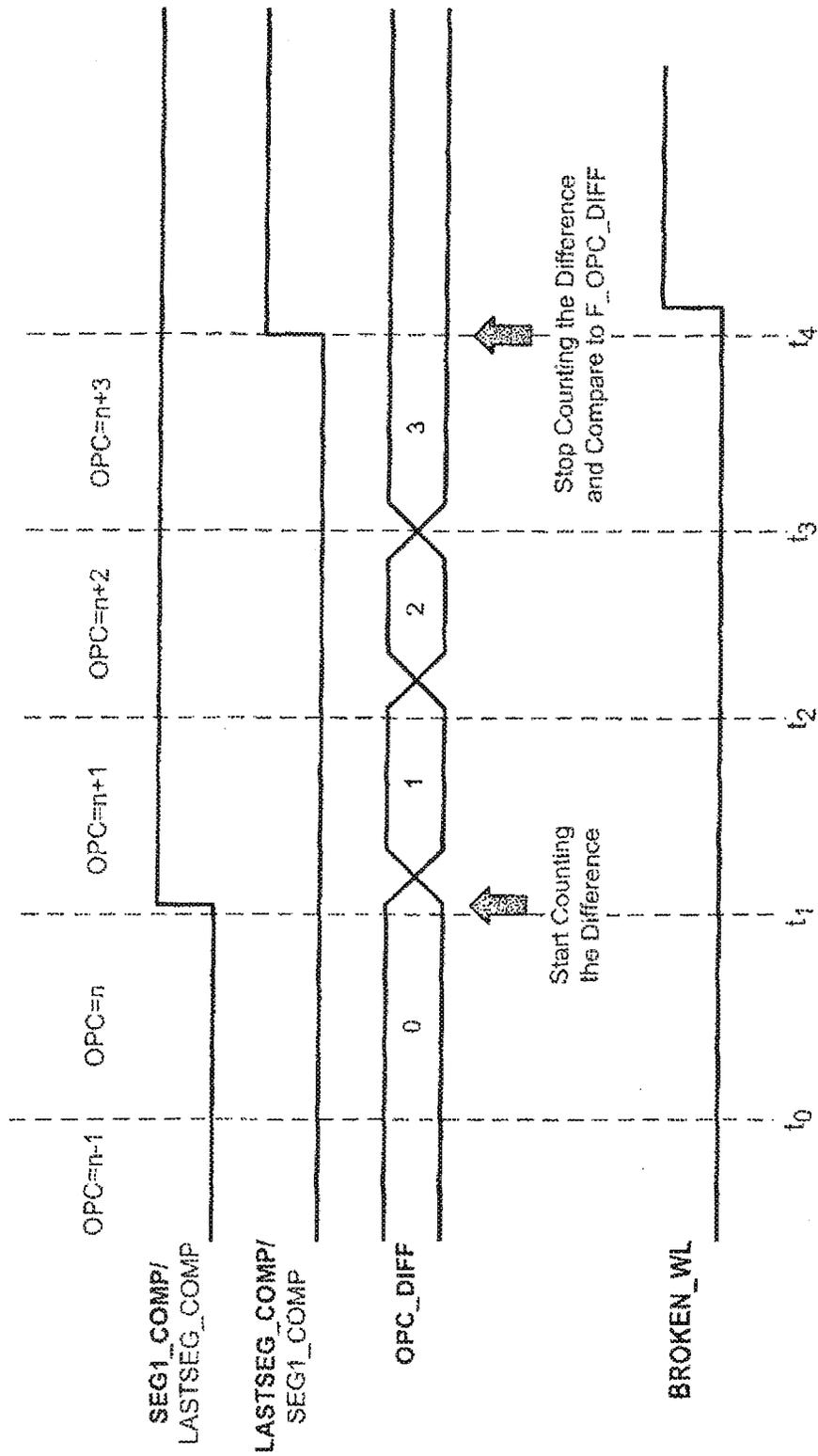


FIG. 20

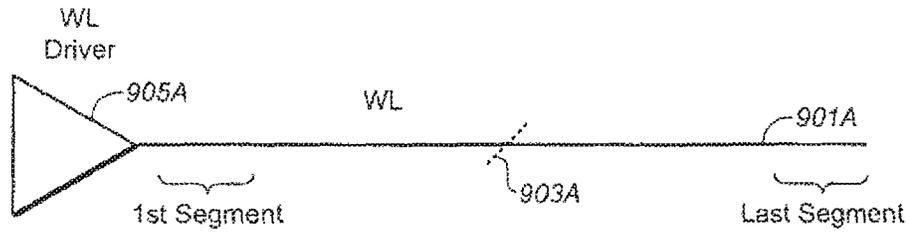


FIG. 21A

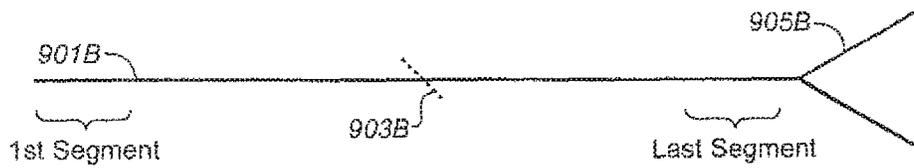


FIG. 21B

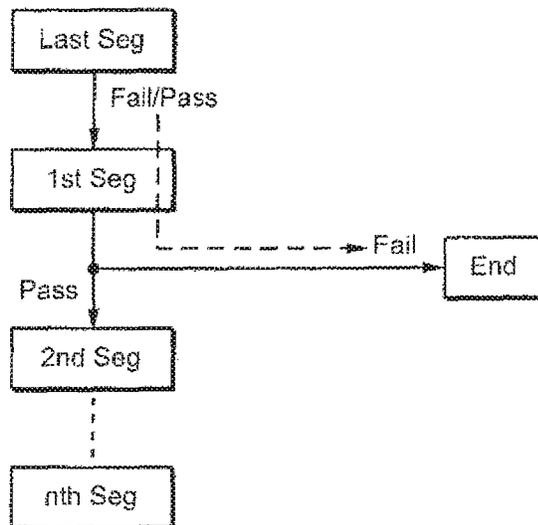


FIG. 22

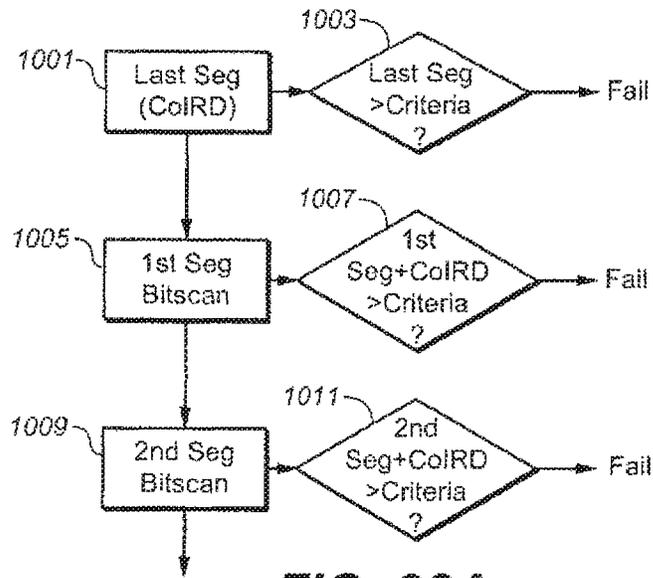


FIG. 23A

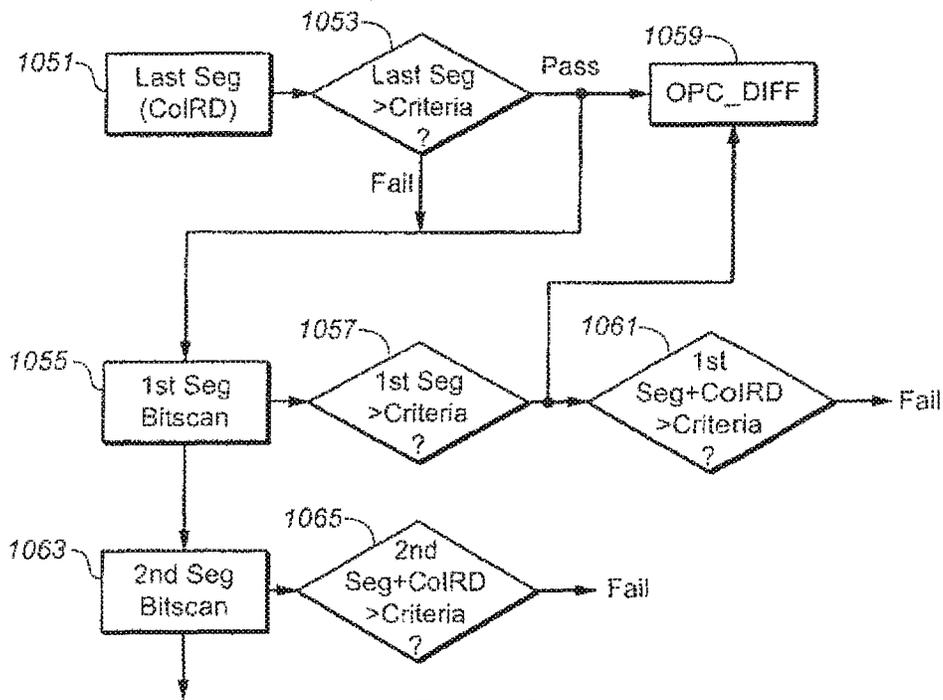


FIG. 23B

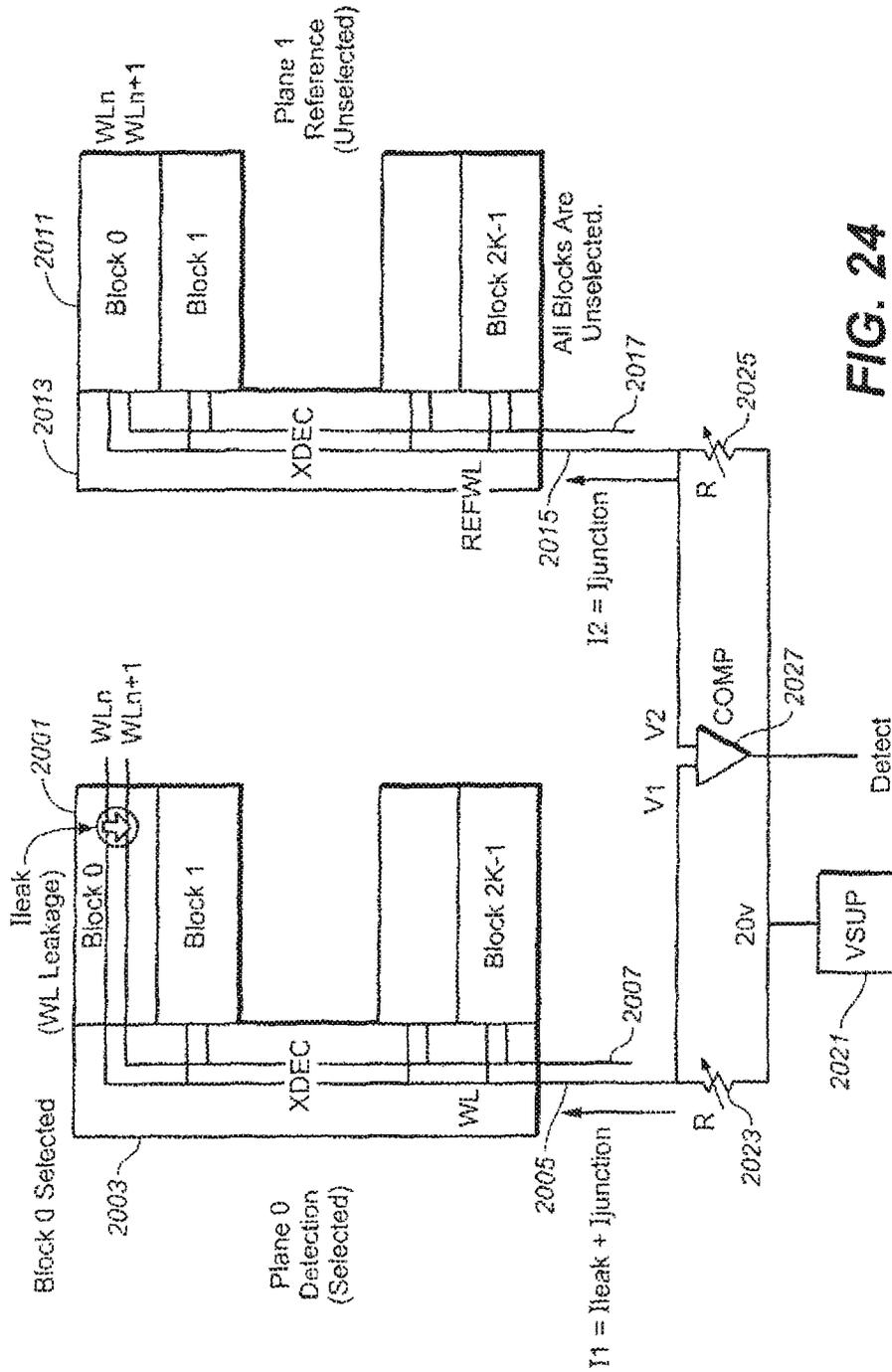


FIG. 24

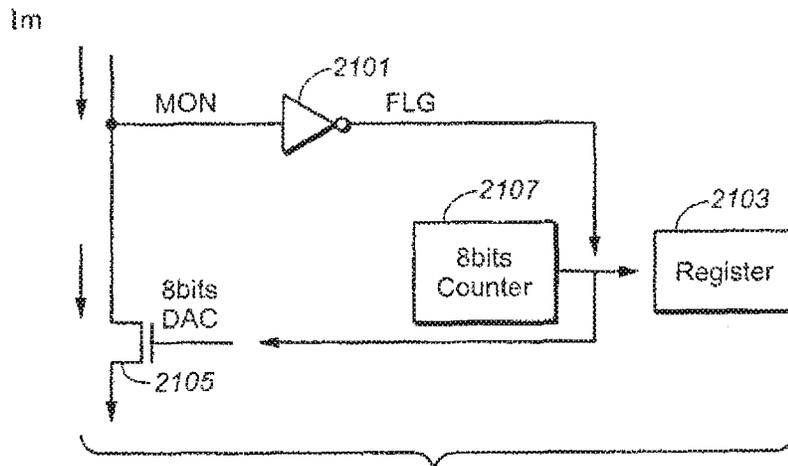


FIG. 25

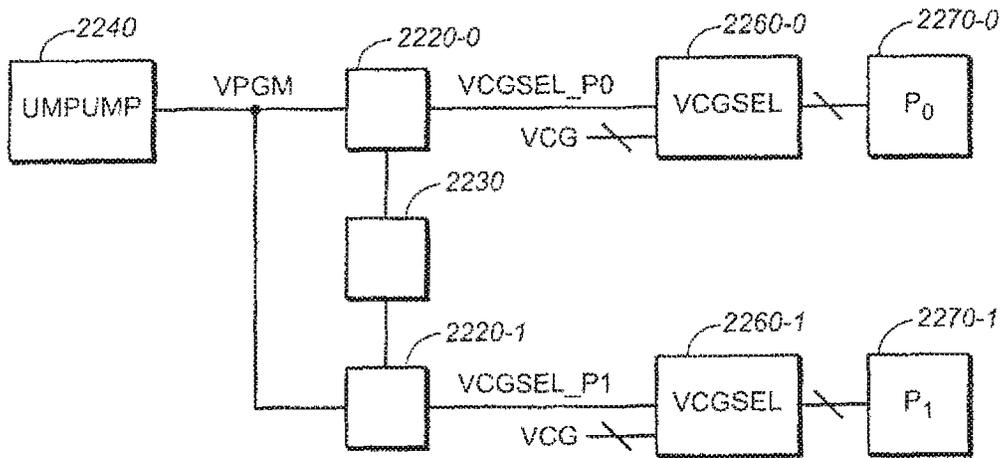


FIG. 27

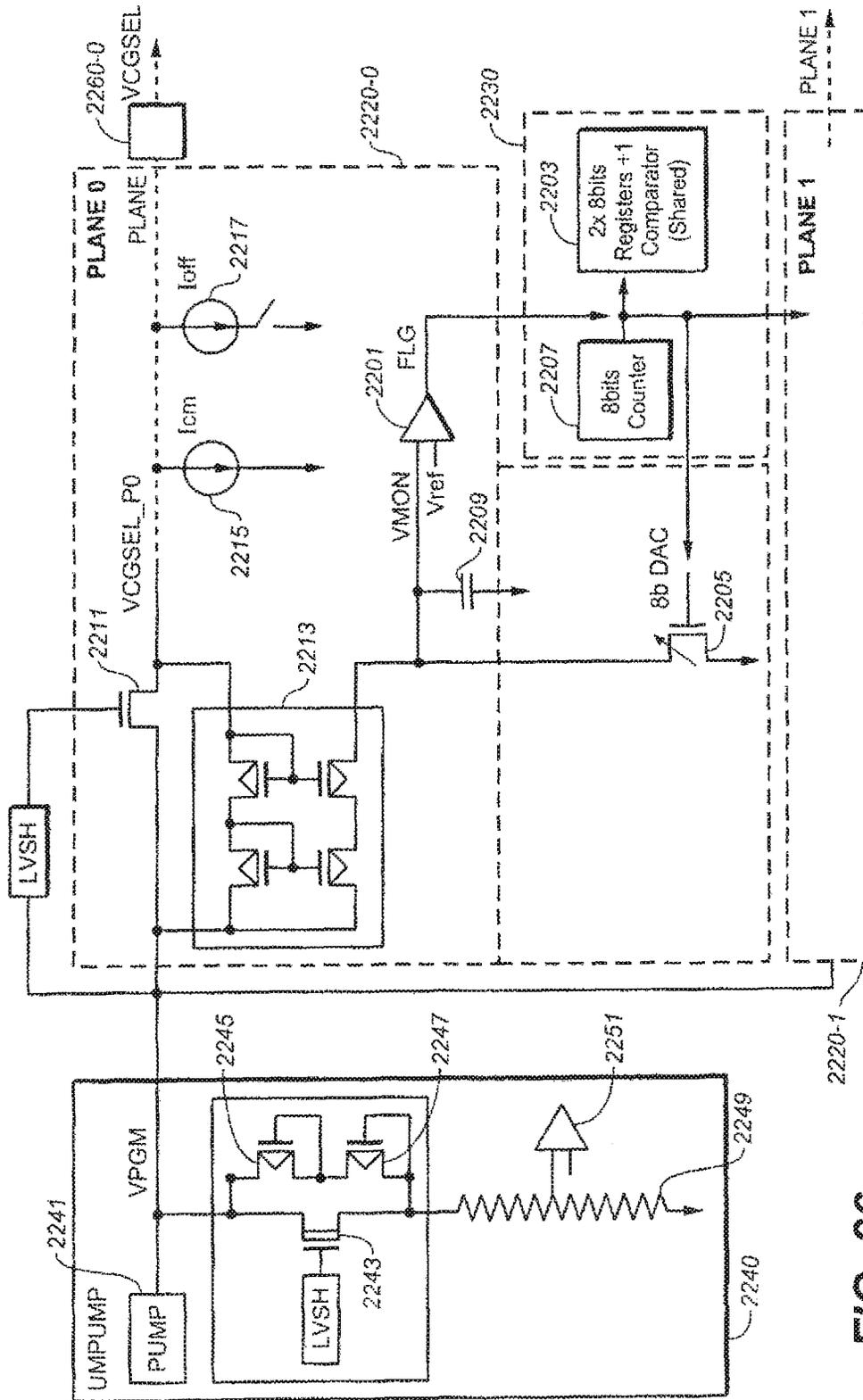


FIG. 26

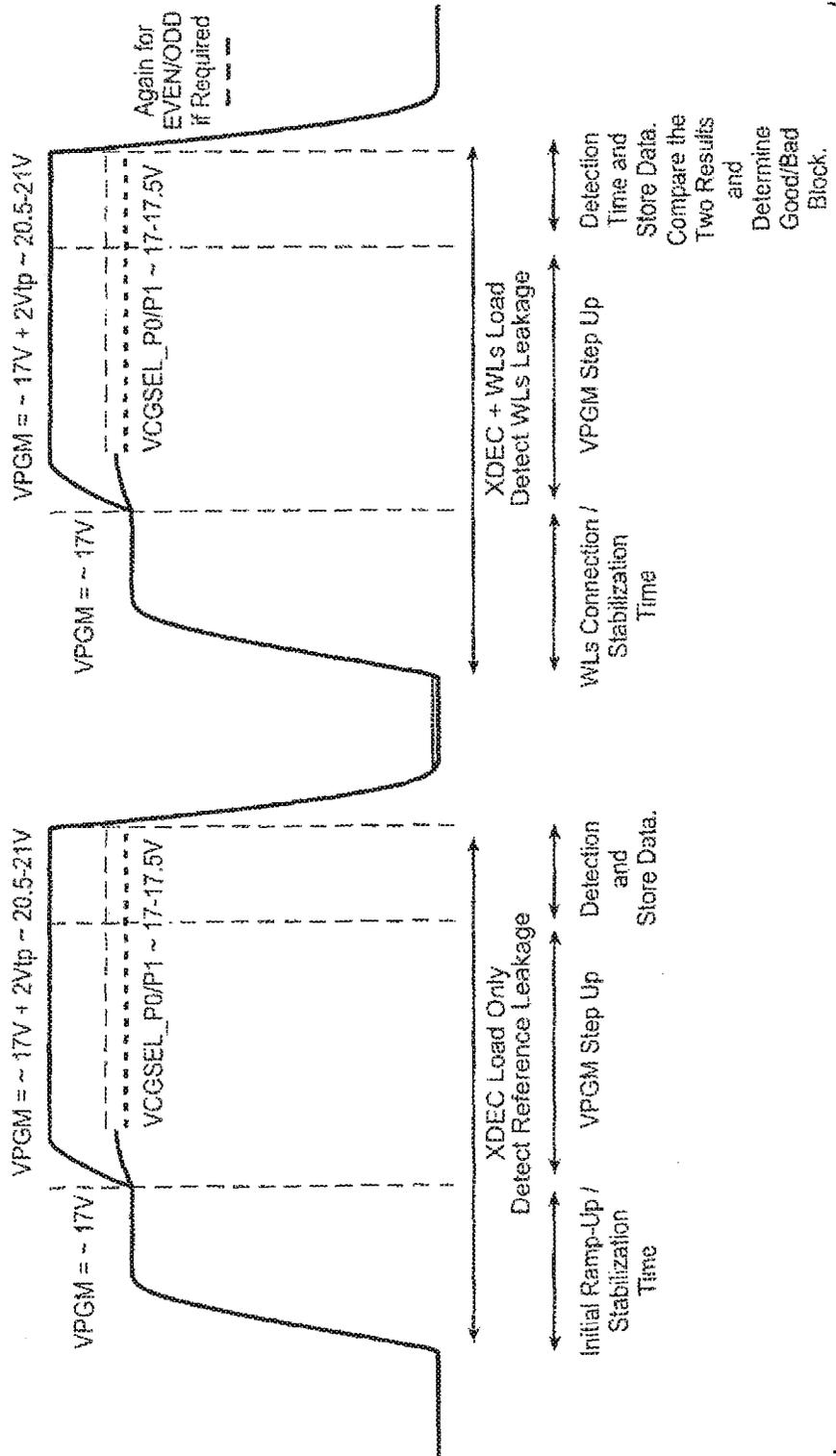


FIG. 28

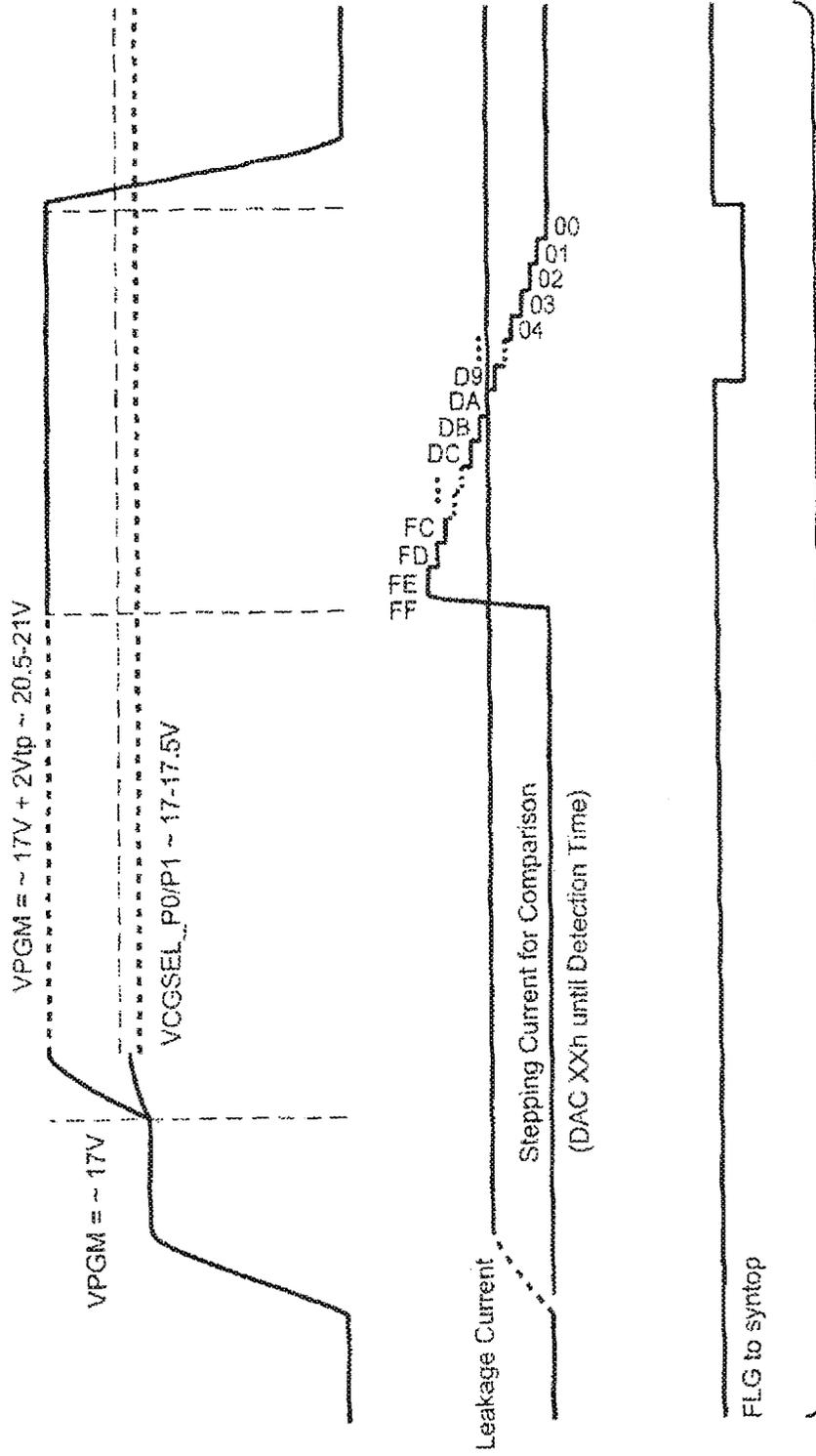


FIG. 29

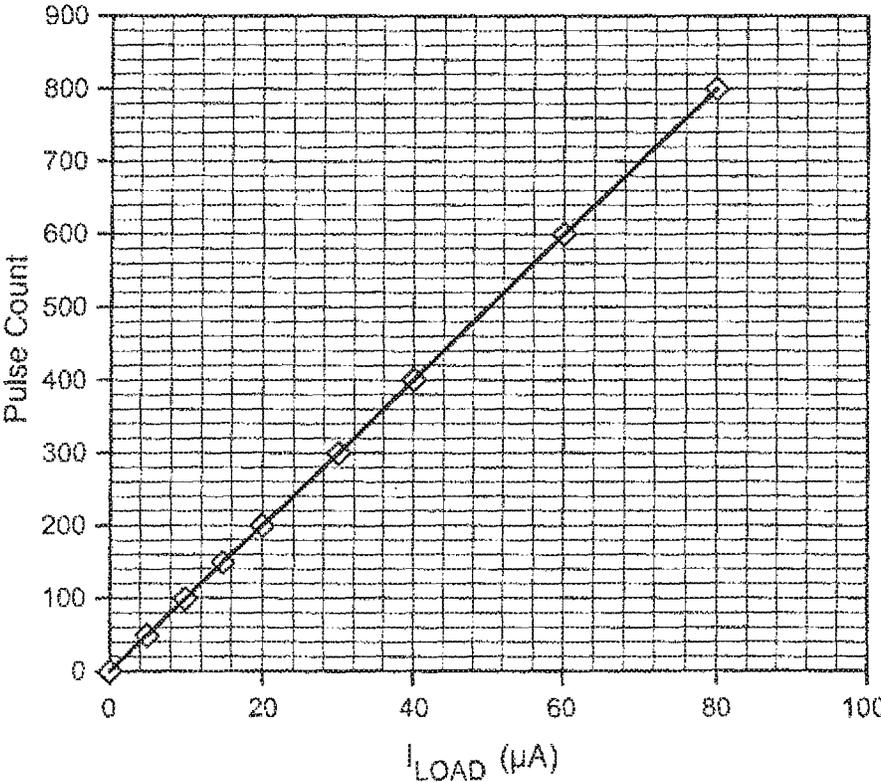


FIG. 30

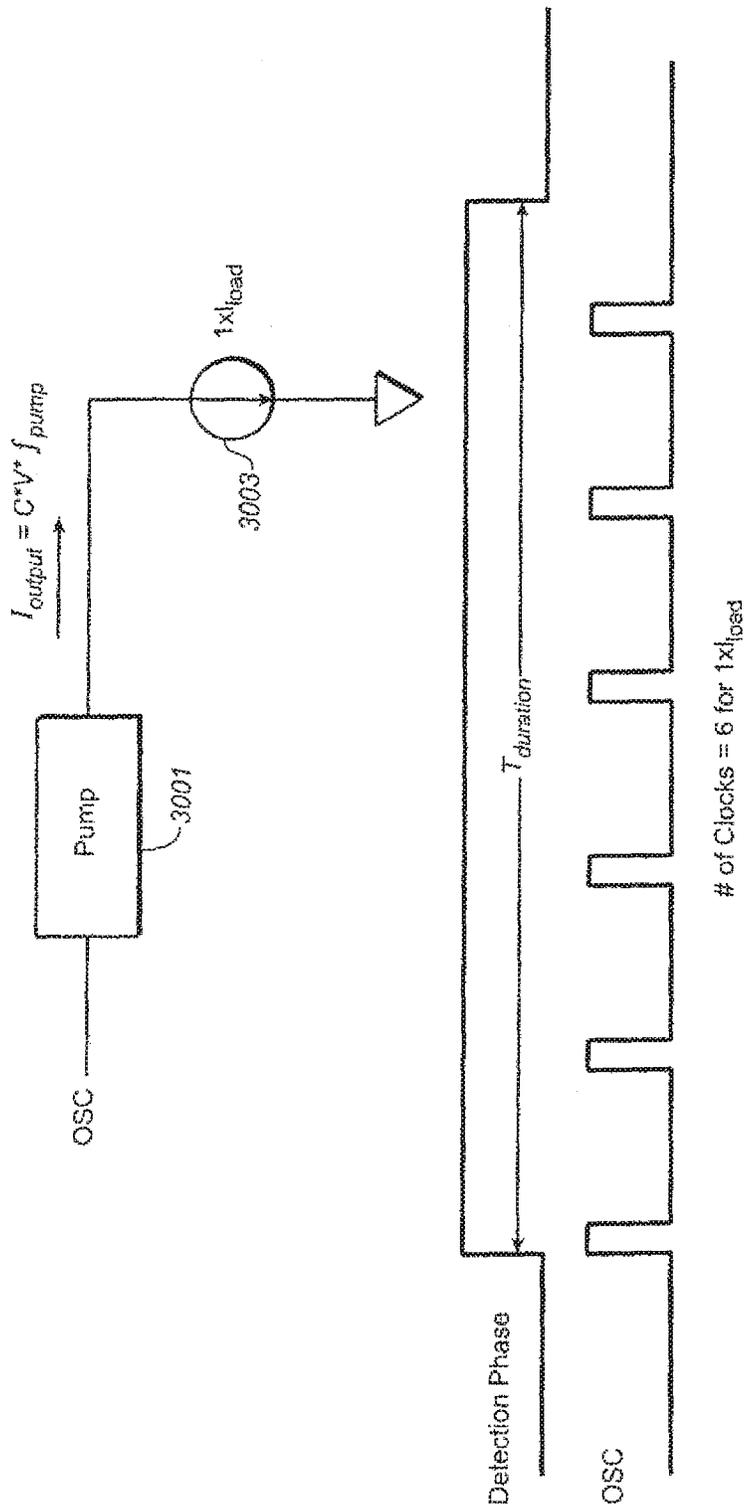


FIG. 31

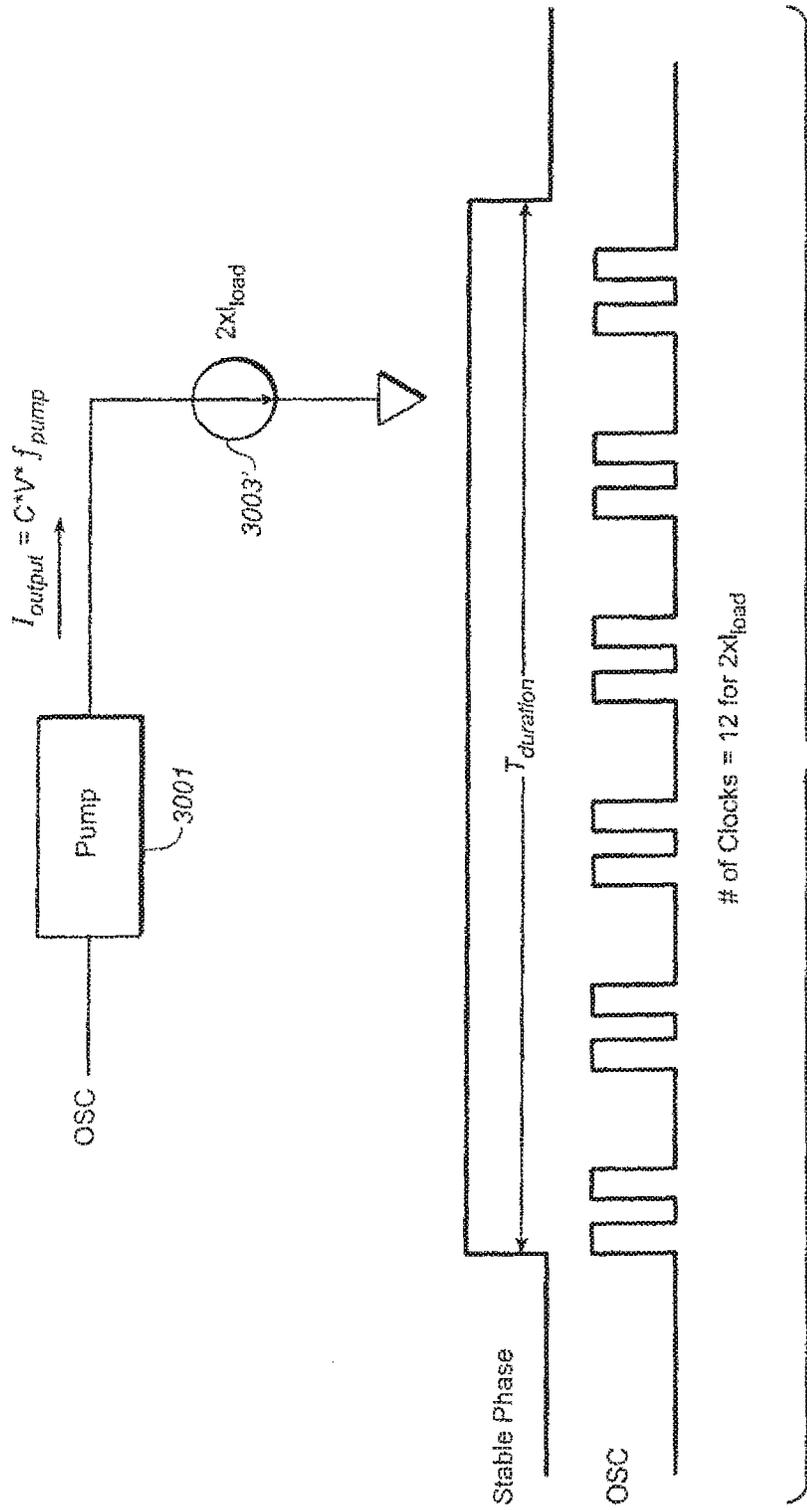


FIG. 32

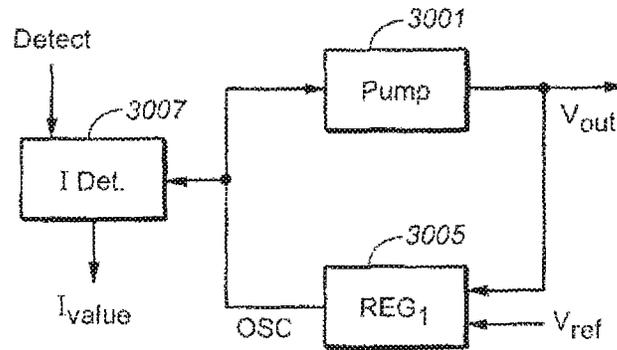


FIG. 33

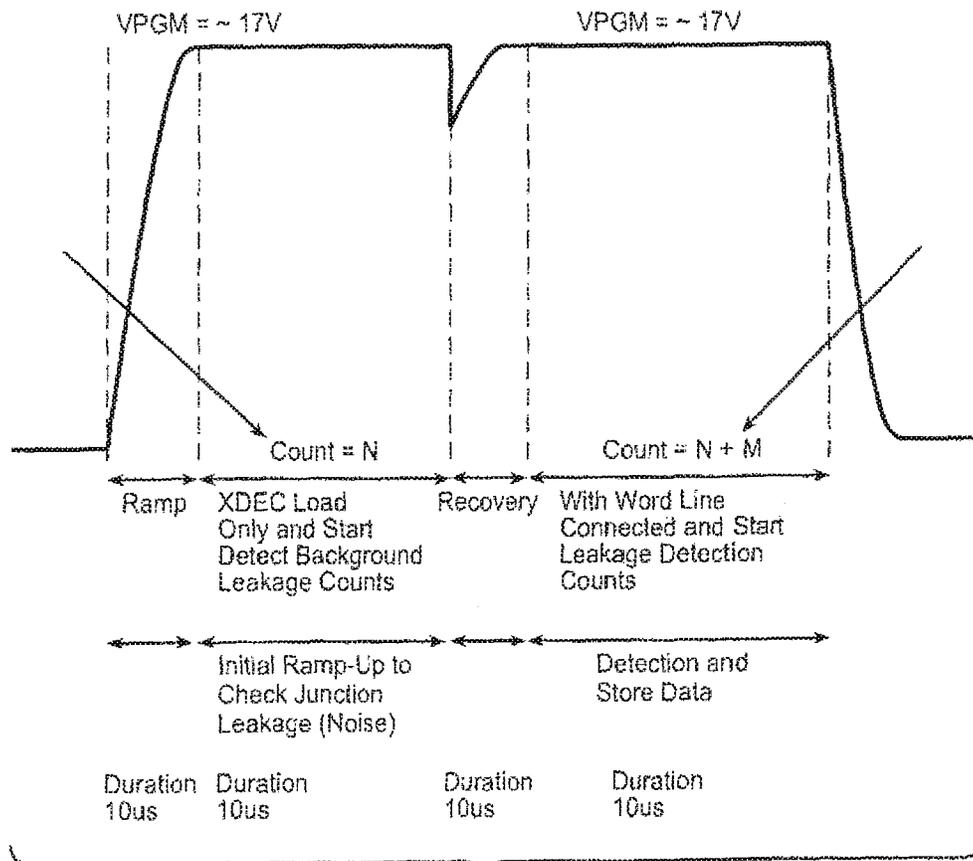


FIG. 34

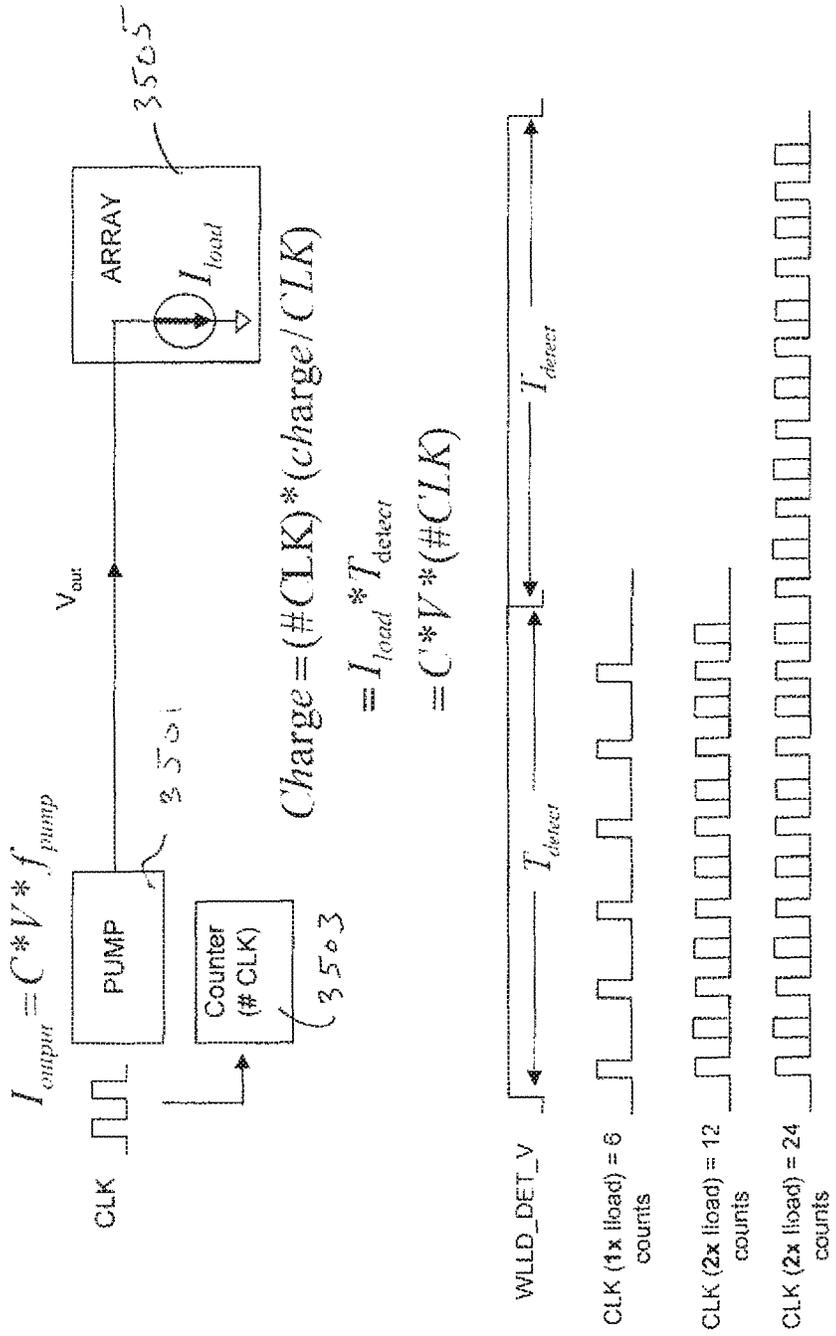


FIG. 35

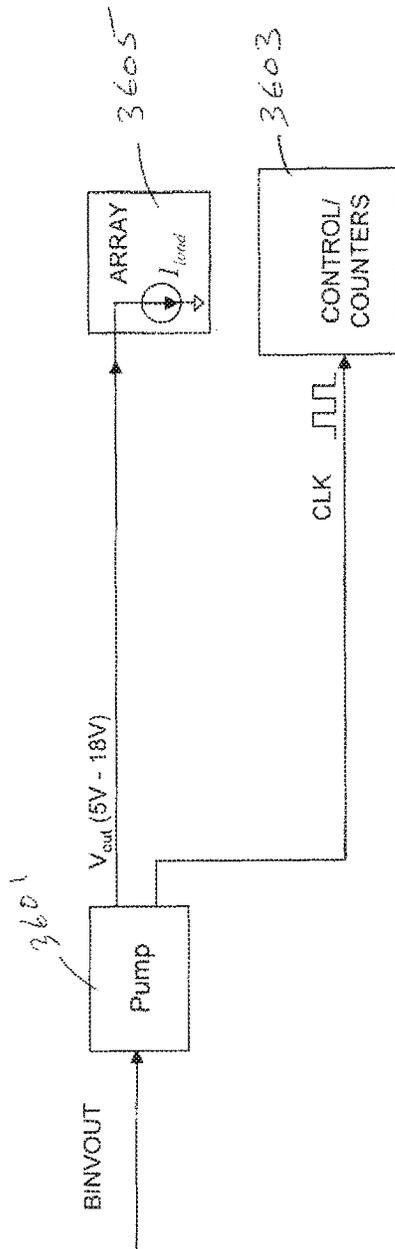


FIG. 36A

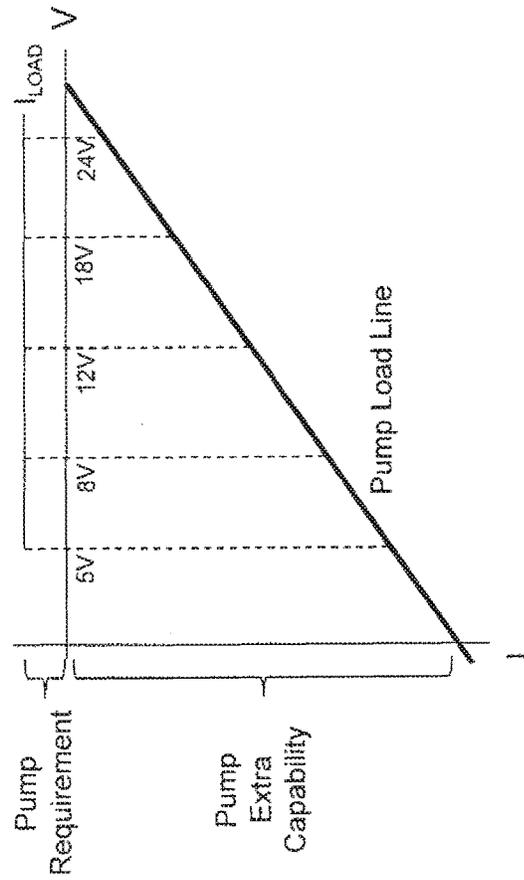


FIG. 36B

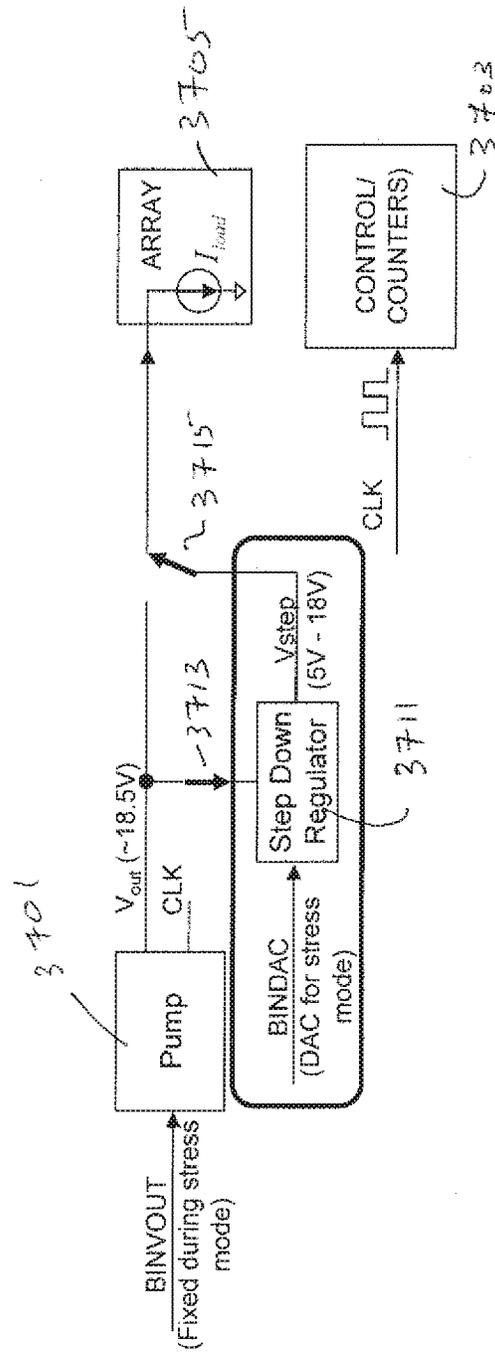


FIG. 37

**CHARGE PUMP BASED OVER-SAMPLING
WITH UNIFORM STEP SIZE FOR CURRENT
DETECTION**

BACKGROUND

The following relates generally to the determining current levels and, more specifically, to the use of the regulation behavior of charge pumps for determining current levels.

Solid-state memory capable of nonvolatile storage of charge, particularly in the form of EEPROM and flash EEPROM packaged as a small form factor card, has recently become the storage of choice in a variety of mobile and handheld devices, notably information appliances and consumer electronics products. Unlike RAM (random access memory) that is also solid-state memory, flash memory is non-volatile and retains its stored data even after power is turned off. In spite of the higher cost, flash memory is increasingly being used in mass storage applications. Conventional mass storage, based on rotating magnetic medium such as hard drives and floppy disks, is unsuitable for the mobile and handheld environment. This is because disk drives tend to be bulky, are prone to mechanical failure and have high latency and high power requirements. These undesirable attributes make disk-based storage impractical in most mobile and portable applications. On the other hand, flash memory, both embedded and in the form of a removable card, are ideally suited in the mobile and handheld environment because of its small size, low power consumption, high speed and high reliability features.

EEPROM and electrically programmable read-only memory (EPROM) are non-volatile memory that can be erased and have new data written or "programmed" into their memory cells. Both utilize a floating (unconnected) conductive gate, in a field effect transistor structure, positioned over a channel region in a semiconductor substrate, between source and drain regions. A control gate is then provided over the floating gate. The threshold voltage characteristic of the transistor is controlled by the amount of charge that is retained on the floating gate. That is, for a given level of charge on the floating gate, there is a corresponding voltage (threshold) that must be applied to the control gate before the transistor is turned "on" to permit conduction between its source and drain regions.

The floating gate can hold a range of charges and therefore can be programmed to any threshold voltage level within a threshold voltage window. The size of the threshold voltage window is delimited by the minimum and maximum threshold levels of the device, which in turn correspond to the range of the charges that can be programmed onto the floating gate. The threshold window generally depends on the memory device's characteristics, operating conditions and history. Each distinct, resolvable threshold voltage level range within the window may, in principle, be used to designate a definite memory state of the cell. When the threshold voltage is partitioned into two distinct regions, each memory cell will be able to store one bit of data. Similarly, when the threshold voltage window is partitioned into more than two distinct regions, each memory cell will be able to store more than one bit of data.

In the usual two-state EEPROM cell, at least one current breakpoint level is established so as to partition the conduction window into two regions. When a cell is read by applying predetermined, fixed voltages, its source/drain current is resolved into a memory state by comparing with the breakpoint level (or reference current IREF). If the current read is higher than that of the breakpoint level, the cell is

determined to be in one logical state (e.g., a "zero" state). On the other hand, if the current is less than that of the breakpoint level, the cell is determined to be in the other logical state (e.g., a "one" state). Thus, such a two-state cell stores one bit of digital information. A reference current source, which may be externally programmable, is often provided as part of a memory system to generate the breakpoint level current.

In order to increase memory capacity, flash EEPROM devices are being fabricated with higher and higher density as the state of the semiconductor technology advances. Another method for increasing storage capacity is to have each memory cell store more than two states.

For a multi-state or multi-level EEPROM memory cell, the conduction window is partitioned into more than two regions by more than one breakpoint such that each cell is capable of storing more than one bit of data. The information that a given EEPROM array can store is thus increased with the number of states that each cell can store.

The transistor serving as a memory cell is typically programmed to a "programmed" state by one of two mechanisms. In "hot electron injection," a high voltage applied to the drain accelerates electrons across the substrate channel region. At the same time a high voltage applied to the control gate pulls the hot electrons through a thin gate dielectric onto the floating gate. In "tunneling injection," a high voltage is applied to the control gate relative to the substrate. In this way, electrons are pulled from the substrate to the intervening floating gate.

The memory device may be erased by a number of mechanisms. For EPROM, the memory is bulk erasable by removing the charge from the floating gate by ultraviolet radiation. For EEPROM, a memory cell is electrically erasable, by applying a high voltage to the substrate relative to the control gate so as to induce electrons in the floating gate to tunnel through a thin oxide to the substrate channel region (i.e., Fowler-Nordheim tunneling.) Typically, the EEPROM is erasable byte by byte. For flash EEPROM, the memory is electrically erasable either all at once or one or more blocks at a time, where a block may consist of 512 bytes or more of memory.

The memory devices typically comprise one or more memory chips that may be mounted on a card. Each memory chip comprises an array of memory cells supported by peripheral circuits such as decoders and erase, write and read circuits. The more sophisticated memory devices operate with an external memory controller that performs intelligent and higher level memory operations and interfacing.

Defects often occur in such memory systems, both as part of the manufacturing process as well over the operating life of the device. One of the sources of such defects are the word-lines of such memory arrays, due both to word-line leakage (to another work-line or to the substrate) and to broken word-lines. These word-line related problems typically become more and more acute as device sizes scale down. Some word-line to word-line leakage does not manifest itself when the device is fresh, but only results in a failure after the stress of a number of program-erase cycles. This leakage will cause the faulty word-line to fail to program and corresponding data will be corrupted. A broken word-line will have a high resistive connection, as a result of which the cells on far end of the break will see a voltage drop during program and verify operations. As a result, the threshold voltage distribution for the broken word-line will show un-distinguishable states. Consequently, both of these sorts of defects can be detrimental to memory operation if not detected.

SUMMARY

A circuit includes a charge pump and regulation circuitry connected to receive an output voltage of the charge pump and regulate the output voltage of the charge pump at a first voltage level by varying a frequency of an oscillator signal supplied to the charge pump. A step down regulator is connected to receive a control signal and connectable to receive the output voltage of the charge pump and generate from it one of a plurality of regulator output voltage levels having a value dependent upon a level of the control signal. The step down regulator is also connectable to drive a load with the one of the regulator output voltage levels. The circuit further includes current detection circuitry connectable to the regulation circuitry to determine a number of cycles of the oscillator supplied to the charge pump during an interval of a first duration in order to maintain the output of the charge pump under regulation at the first voltage level while driving the load at the one of the regulator output voltage levels. From the determined number of cycles, an amount of current being drawn by the load is determined.

In method of determining an amount of current being drawn by a load, a charge pump generates an output voltage and regulation circuitry connected to receive the output voltage regulates the output voltage at a first voltage level by varying a frequency of an oscillator signal it supplies to the charge pump. A step down regulator receives a control signal and, while the output voltage regulated at the first voltage level is being generated, the output voltage. From the output voltage, the step down generator generates a second voltage level having a value dependent upon a level of the control signal and drives the load with the second voltage level. While driving the load with the second voltage level, the method determines a number of cycles of the oscillator supplied to the charge pump during an interval of a first duration in order to maintain the output of the charge pump regulated at the first voltage level. The determined number of cycles is compared to a reference value and, based upon the comparison, determining the amount of current being drawn by the load is determined.

A memory circuit includes a memory array, a charge pump system, a step down regulator and current detection circuitry. The charge pump system includes a charge pump and regulation circuitry connected to receive an output voltage of the charge pump and regulate the output voltage of the charge pump at a first voltage level by varying a frequency of an oscillator signal supplied to the charge pump. The step down regulator is connected to receive a control signal and is connectable to receive the output voltage of the charge pump and generate therefrom regulator output voltage level having a value dependent upon a level of the control signal. The step down regulator is further connectable to drive a bias line of the array with the regulator output voltage level. The current detection circuitry is connectable to the charge pump system to determine a number of cycles of the oscillator supplied to the charge pump during an interval of a first duration in order to maintain the output of the charge pump under regulation at the first voltage level while driving the bias line of the array at the regulator output voltage level and, from the determined number of cycles, determine an amount of current being drawn by the bias line of the array.

Various aspects, advantages, features and embodiments are included in the following description of exemplary examples thereof, which description should be taken in conjunction with the accompanying drawings. All patents, patent applications, articles, other publications, documents

and things referenced herein are hereby incorporated herein by this reference in their entirety for all purposes. To the extent of any inconsistency or conflict in the definition or use of terms between any of the incorporated publications, documents or things and the present application, those of the present application shall prevail.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates schematically the main hardware components of a memory system suitable for implementing various aspects described in the following.

FIG. 2 illustrates schematically a non-volatile memory cell.

FIG. 3 illustrates the relation between the source-drain current I_D and the control gate voltage V_{CG} for four different charges Q1-Q4 that the floating gate may be selectively storing at any one time at fixed drain voltage.

FIG. 4 illustrates schematically a string of memory cells organized into a NAND string.

FIG. 5 illustrates an example of a NAND array 210 of memory cells, constituted from NAND strings 50 such as that shown in FIG. 4.

FIG. 6 illustrates a page of memory cells, organized in the NAND configuration, being sensed or programmed in parallel.

FIGS. 7A-7C illustrate an example of programming a population of memory cells.

FIG. 8 shows an example of a physical structure of a 3-D NAND string.

FIGS. 9-12 look at a particular monolithic three dimensional (3D) memory array of the NAND type (more specifically of the "BiCS" type).

FIG. 13 shows a circuitry detail on how voltages are supplied to word-lines.

FIG. 14A is a block diagram of an exemplary charge pump circuit.

FIG. 14B adds leakage detection circuitry to FIG. 14A.

FIG. 15 illustrates the phases of the exemplary leakage detection operation.

FIG. 16 shows the current path in a calibration process for the word-line leakage process.

FIG. 17 illustrates the phases of the calibration operation.

FIG. 18 shows the distribution of memory cell threshold voltage values to illustrate symptoms of a broken word-line.

FIG. 19 illustrates the variation in the number of programming pulse-verify iterations over different word-lines.

FIG. 20 is a timing diagram for a broken word-line detection routine.

FIGS. 21A and 21B illustrate differing placements of word-line drivers.

FIGS. 22 and 23A are flows for a scan of failed bits in a program operation.

FIG. 23B is a flow for a scan of failed bits in a program operation that also includes broken word-line detection.

FIG. 24 illustrates a current based comparison for leakage determination where two different arrays are used, one unselected and for reference use and one with an erase block selected for testing.

FIG. 25 illustrates the basic operation of exemplary circuitry for determining a leakage current level.

FIG. 26 shows the elements from FIG. 25 along with some of the other elements used in the exemplary embodiment for the leakage determination circuitry.

FIG. 27 is a block diagram to schematically illustrate the relationship of the elements of FIG. 26 to two planes.

FIG. 28 is a timing diagram for one particular implementation of the leakage determination operation.

FIG. 29 adds leakage current determination elements to the part of the waveform of FIG. 28.

FIG. 30 is plot of load versus pulse count for a charge pump system driving a load under regulation within a fixed duration.

FIG. 31 schematically illustrates a charge pump drive a load.

FIG. 32 schematically illustrates a charge pump drive twice the load of FIG. 31.

FIG. 33 is a box diagram of a charge pump system with a current level detection block.

FIG. 34 is a timing diagram for an exemplary embodiment of a pump-based current determination arrangement.

FIG. 35 looks at charge pump and some corresponding waveforms when drive a load at a current level and twice that current level.

FIG. 36A considers when the same pump drives a load at differing output voltages.

FIG. 36B illustrates the load line for the pump of FIG. 36A.

FIG. 37 illustrates the incorporation of a step-down regulator for driving the load.

DETAILED DESCRIPTION

Memory System

FIG. 1 illustrates schematically the main hardware components of a memory system suitable for implementing the following. The memory system 90 typically operates with a host 80 through a host interface. The memory system may be in the form of a removable memory such as a memory card, or may be in the form of an embedded memory system. The memory system 90 includes a memory 102 whose operations are controlled by a controller 100. The memory 102 comprises one or more array of non-volatile memory cells distributed over one or more integrated circuit chip. The controller 100 may include interface circuits 110, a processor 120, ROM (read-only-memory) 122, RAM (random access memory) 130, programmable nonvolatile memory 124, and additional components. The controller is typically formed as an ASIC (application specific integrated circuit) and the components included in such an ASIC generally depend on the particular application.

With respect to the memory section 102, semiconductor memory devices include volatile memory devices, such as dynamic random access memory ("DRAM") or static random access memory ("SRAM") devices, non-volatile memory devices, such as resistive random access memory ("ReRAM"), electrically erasable programmable read only memory ("EEPROM"), flash memory (which can also be considered a subset of EEPROM), ferroelectric random access memory ("FRAM"), and magnetoresistive random access memory ("MRAM"), and other semiconductor elements capable of storing information. Each type of memory device may have different configurations. For example, flash memory devices may be configured in a NAND or a NOR configuration.

The memory devices can be formed from passive and/or active elements, in any combinations. By way of non-limiting example, passive semiconductor memory elements include ReRAM device elements, which in some embodiments include a resistivity switching storage element, such as an anti-fuse, phase change material, etc., and optionally a steering element, such as a diode, etc. Further by way of

non-limiting example, active semiconductor memory elements include EEPROM and flash memory device elements, which in some embodiments include elements containing a charge storage region, such as a floating gate, conductive nanoparticles, or a charge storage dielectric material.

Multiple memory elements may be configured so that they are connected in series or so that each element is individually accessible. By way of non-limiting example, flash memory devices in a NAND configuration (NAND memory) typically contain memory elements connected in series. A NAND memory array may be configured so that the array is composed of multiple strings of memory in which a string is composed of multiple memory elements sharing a single bit line and accessed as a group. Alternatively, memory elements may be configured so that each element is individually accessible, e.g., a NOR memory array. NAND and NOR memory configurations are exemplary, and memory elements may be otherwise configured.

The semiconductor memory elements located within and/or over a substrate may be arranged in two or three dimensions, such as a two dimensional memory structure or a three dimensional memory structure.

In a two dimensional memory structure, the semiconductor memory elements are arranged in a single plane or a single memory device level. Typically, in a two dimensional memory structure, memory elements are arranged in a plane (e.g., in an x-z direction plane) which extends substantially parallel to a major surface of a substrate that supports the memory elements. The substrate may be a wafer over or in which the layer of the memory elements are formed or it may be a carrier substrate which is attached to the memory elements after they are formed. As a non-limiting example, the substrate may include a semiconductor such as silicon.

The memory elements may be arranged in the single memory device level in an ordered array, such as in a plurality of rows and/or columns. However, the memory elements may be arrayed in non-regular or non-orthogonal configurations. The memory elements may each have two or more electrodes or contact lines, such as bit lines and word lines.

A three dimensional memory array is arranged so that memory elements occupy multiple planes or multiple memory device levels, thereby forming a structure in three dimensions (i.e., in the x, y and z directions, where the y direction is substantially perpendicular and the x and z directions are substantially parallel to the major surface of the substrate).

As a non-limiting example, a three dimensional memory structure may be vertically arranged as a stack of multiple two dimensional memory device levels. As another non-limiting example, a three dimensional memory array may be arranged as multiple vertical columns (e.g., columns extending substantially perpendicular to the major surface of the substrate, i.e., in the y direction) with each column having multiple memory elements in each column. The columns may be arranged in a two dimensional configuration, e.g., in an x-z plane, resulting in a three dimensional arrangement of memory elements with elements on multiple vertically stacked memory planes. Other configurations of memory elements in three dimensions can also constitute a three dimensional memory array.

By way of non-limiting example, in a three dimensional NAND memory array, the memory elements may be coupled together to form a NAND string within a single horizontal (e.g., x-z) memory device levels. Alternatively, the memory elements may be coupled together to form a vertical NAND string that traverses across multiple horizontal memory

device levels. Other three dimensional configurations can be envisioned wherein some NAND strings contain memory elements in a single memory level while other strings contain memory elements which span through multiple memory levels. Three dimensional memory arrays may also be designed in a NOR configuration and in a ReRAM configuration.

Typically, in a monolithic three dimensional memory array, one or more memory device levels are formed above a single substrate. Optionally, the monolithic three dimensional memory array may also have one or more memory layers at least partially within the single substrate. As a non-limiting example, the substrate may include a semiconductor such as silicon. In a monolithic three dimensional array, the layers constituting each memory device level of the array are typically formed on the layers of the underlying memory device levels of the array. However, layers of adjacent memory device levels of a monolithic three dimensional memory array may be shared or have intervening layers between memory device levels.

Then again, two dimensional arrays may be formed separately and then packaged together to form a non-monolithic memory device having multiple layers of memory. For example, non-monolithic stacked memories can be constructed by forming memory levels on separate substrates and then stacking the memory levels atop each other. The substrates may be thinned or removed from the memory device levels before stacking, but as the memory device levels are initially formed over separate substrates, the resulting memory arrays are not monolithic three dimensional memory arrays. Further, multiple two dimensional memory arrays or three dimensional memory arrays (monolithic or non-monolithic) may be formed on separate chips and then packaged together to form a stacked-chip memory device.

Associated circuitry is typically required for operation of the memory elements and for communication with the memory elements. As non-limiting examples, memory devices may have circuitry used for controlling and driving memory elements to accomplish functions such as programming and reading. This associated circuitry may be on the same substrate as the memory elements and/or on a separate substrate. For example, a controller for memory read-write operations may be located on a separate controller chip and/or on the same substrate as the memory elements.

It will be recognized that the following is not limited to the two dimensional and three dimensional exemplary structures described but cover all relevant memory structures within the spirit and scope as described herein

Physical Memory Structure

FIG. 2 illustrates schematically a non-volatile memory cell. The memory cell 10 can be implemented by a field-effect transistor having a charge storage unit 20, such as a floating gate or a charge trapping (dielectric) layer. The memory cell 10 also includes a source 14, a drain 16, and a control gate 30.

There are many commercially successful non-volatile solid-state memory devices being used today. These memory devices may employ different types of memory cells, each type having one or more charge storage element.

Typical non-volatile memory cells include EEPROM and flash EEPROM. Also, examples of memory devices utilizing dielectric storage elements.

In practice, the memory state of a cell is usually read by sensing the conduction current across the source and drain electrodes of the cell when a reference voltage is applied to the control gate. Thus, for each given charge on the floating

gate of a cell, a corresponding conduction current with respect to a fixed reference control gate voltage may be detected. Similarly, the range of charge programmable onto the floating gate defines a corresponding threshold voltage window or a corresponding conduction current window.

Alternatively, instead of detecting the conduction current among a partitioned current window, it is possible to set the threshold voltage for a given memory state under test at the control gate and detect if the conduction current is lower or higher than a threshold current (cell-read reference current). In one implementation the detection of the conduction current relative to a threshold current is accomplished by examining the rate the conduction current is discharging through the capacitance of the bit line.

FIG. 3 illustrates the relation between the source-drain current I_D and the control gate voltage V_{CG} for four different charges Q1-Q4 that the floating gate may be selectively storing at any one time. With fixed drain voltage bias, the four solid I_D versus V_{CG} curves represent four of seven possible charge levels that can be programmed on a floating gate of a memory cell, respectively corresponding to four possible memory states. As an example, the threshold voltage window of a population of cells may range from 0.5V to 3.5V. Seven possible programmed memory states "0", "1", "2", "3", "4", "5", "6", and an erased state (not shown) may be demarcated by partitioning the threshold window into regions in intervals of 0.5V each. For example, if a reference current, I_{REF} of 2 μ A is used as shown, then the cell programmed with Q1 may be considered to be in a memory state "1" since its curve intersects with I_{REF} in the region of the threshold window demarcated by $V_{CG}=0.5V$ and 1.0V. Similarly, Q4 is in a memory state "5".

As can be seen from the description above, the more states a memory cell is made to store, the more finely divided is its threshold window. For example, a memory device may have memory cells having a threshold window that ranges from -1.5V to 5V. This provides a maximum width of 6.5V. If the memory cell is to store 16 states, each state may occupy from 200 mV to 300 mV in the threshold window. This will require higher precision in programming and reading operations in order to be able to achieve the required resolution.

NAND Structure

FIG. 4 illustrates schematically a string of memory cells organized into a NAND string. A NAND string 50 comprises a series of memory transistors M1, M2, . . . Mn (e.g., n=4, 8, 16 or higher) daisy-chained by their sources and drains. A pair of select transistors S1, S2 controls the memory transistor chain's connection to the external world via the NAND string's source terminal 54 and drain terminal 56 respectively. In a memory array, when the source select transistor S1 is turned on, the source terminal is coupled to a source line (see FIG. 5). Similarly, when the drain select transistor S2 is turned on, the drain terminal of the NAND string is coupled to a bit line of the memory array. Each memory transistor 10 in the chain acts as a memory cell. It has a charge storage element 20 to store a given amount of charge so as to represent an intended memory state. A control gate 30 of each memory transistor allows control over read and write operations. As will be seen in FIG. 5, the control gates 30 of corresponding memory transistors of a row of NAND string are all connected to the same word line. Similarly, a control gate 32 of each of the select transistors S1, S2 provides control access to the NAND string via its source terminal 54 and drain terminal 56 respectively. Likewise, the control gates 32 of corresponding select transistors of a row of NAND string are all connected to the same select line.

When an addressed memory transistor **10** within a NAND string is read or is verified during programming, its control gate **30** is supplied with an appropriate voltage. At the same time, the rest of the non-addressed memory transistors in the NAND string **50** are fully turned on by application of sufficient voltage on their control gates. In this way, a conductive path is effectively created from the source of the individual memory transistor to the source terminal **54** of the NAND string and likewise for the drain of the individual memory transistor to the drain terminal **56** of the cell.

FIG. 4B illustrates an example of a NAND array **210** of memory cells, constituted from NAND strings **50** such as that shown in FIG. 4. Along each column of NAND strings, a bit line such as bit line **36** is coupled to the drain terminal **56** of each NAND string. Along each bank of NAND strings, a source line such as source line **34** is coupled to the source terminals **54** of each NAND string. Also the control gates along a row of memory cells in a bank of NAND strings are connected to a word line such as word line **42**. The control gates along a row of select transistors in a bank of NAND strings are connected to a select line such as select line **44**. An entire row of memory cells in a bank of NAND strings can be addressed by appropriate voltages on the word lines and select lines of the bank of NAND strings.

FIG. 6 illustrates a page of memory cells, organized in the NAND configuration, being sensed or programmed in parallel. FIG. 6 essentially shows a bank of NAND strings **50** in the memory array **210** of FIG. 5, where the detail of each NAND string is shown explicitly as in FIG. 4. A physical page, such as the page **60**, is a group of memory cells enabled to be sensed or programmed in parallel. This is accomplished by a corresponding page of sense amplifiers **212**. The sensed results are latched in a corresponding set of latches **214**. Each sense amplifier can be coupled to a NAND string via a bit line. The page is enabled by the control gates of the cells of the page connected in common to a word line **42** and each cell accessible by a sense amplifier accessible via a bit line **36**. As an example, when respectively sensing or programming the page of cells **60**, a sensing voltage or a programming voltage is respectively applied to the common word line **WL3** together with appropriate voltages on the bit lines.

Physical Organization of the Memory

One difference between flash memory and other of types of memory is that a cell must be programmed from the erased state. That is the floating gate must first be emptied of charge. Programming then adds a desired amount of charge back to the floating gate. It does not support removing a portion of the charge from the floating gate to go from a more programmed state to a lesser one. This means that updated data cannot overwrite existing data and must be written to a previous unwritten location.

Furthermore erasing is to empty all the charges from the floating gate and generally takes appreciable time. For that reason, it will be cumbersome and very slow to erase cell by cell or even page by page. In practice, the array of memory cells is divided into a large number of blocks of memory cells. As is common for flash EEPROM systems, the block is the unit of erase. That is, each block contains the minimum number of memory cells that are erased together. While aggregating a large number of cells in a block to be erased in parallel will improve erase performance, a large size block also entails dealing with a larger number of update and obsolete data.

Each block is typically divided into a number of physical pages. A logical page is a unit of programming or reading that contains a number of bits equal to the number of cells

in a physical page. In a memory that stores one bit per cell, one physical page stores one logical page of data. In memories that store two bits per cell, a physical page stores two logical pages. The number of logical pages stored in a physical page thus reflects the number of bits stored per cell. In one embodiment, the individual pages may be divided into segments and the segments may contain the fewest number of cells that are written at one time as a basic programming operation. One or more logical pages of data are typically stored in one row of memory cells. A page can store one or more sectors. A sector includes user data and overhead data.

All-Bit, Full-Sequence MLC Programming

FIG. 7A-7C illustrate an example of programming a population of 4-state memory cells. FIG. 7A illustrates the population of memory cells programmable into four distinct distributions of threshold voltages respectively representing memory states "0", "1", "2" and "3". FIG. 7B illustrates the initial distribution of "erased" threshold voltages for an erased memory. FIG. 7C illustrates an example of the memory after many of the memory cells have been programmed. Essentially, a cell initially has an "erased" threshold voltage and programming will move it to a higher value into one of the three zones demarcated by verify levels vV_1 , vV_2 and vV_3 . In this way, each memory cell can be programmed to one of the three programmed states "1", "2" and "3" or remain un-programmed in the "erased" state. As the memory gets more programming, the initial distribution of the "erased" state as shown in FIG. 7B will become narrower and the erased state is represented by the "0" state.

A 2-bit code having a lower bit and an upper bit can be used to represent each of the four memory states. For example, the "0", "1", "2" and "3" states are respectively represented by "11", "01", "00" and "10". The 2-bit data may be read from the memory by sensing in "full-sequence" mode where the two bits are sensed together by sensing relative to the read demarcation threshold values rV_1 , rV_2 and rV_3 in three sub-passes respectively.

3-D NAND Structures

An alternative arrangement to a conventional two-dimensional (2-D) NAND array is a three-dimensional (3-D) array. In contrast to 2-D NAND arrays, which are formed along a planar surface of a semiconductor wafer, 3-D arrays extend up from the wafer surface and generally include stacks, or columns, of memory cells extending upwards. Various 3-D arrangements are possible. In one arrangement a NAND string is formed vertically with one end (e.g. source) at the wafer surface and the other end (e.g. drain) on top. In another arrangement a NAND string is formed in a U-shape so that both ends of the NAND string are accessible on top, thus facilitating connections between such strings.

FIG. 8 shows a first example of a NAND string **701** that extends in a vertical direction, i.e. extending in the z-direction, perpendicular to the x-y plane of the substrate. Memory cells are formed where a vertical bit line (local bit line) **703** passes through a word line (e.g. **WL0**, **WL1**, etc.). A charge trapping layer between the local bit line and the word line stores charge, which affects the threshold voltage of the transistor formed by the word line (gate) coupled to the vertical bit line (channel) that it encircles. Such memory cells may be formed by forming stacks of word lines and then etching memory holes where memory cells are to be formed. Memory holes are then lined with a charge trapping layer and filled with a suitable local bit line/channel material (with suitable dielectric layers for isolation).

As with planar NAND strings, select gates **705**, **707**, are located at either end of the string to allow the NAND string

to be selectively connected to, or isolated from, external elements 709, 711. Such external elements are generally conductive lines such as common source lines or bit lines that serve large numbers of NAND strings. Vertical NAND strings may be operated in a similar manner to planar NAND strings and both SLC and MLC operation is possible. While FIG. 8 shows an example of a NAND string that has 32 cells (0-31) connected in series, the number of cells in a NAND string may be any suitable number. Not all cells are shown for clarity. It will be understood that additional cells are formed where word lines 3-29 (not shown) intersect the local vertical bit line.

A 3D NAND array can, loosely speaking, be formed tilting up the respective structures 50 and 210 of FIGS. 5 and 6 to be perpendicular to the x-y plane. In this example, each y-z plane corresponds to the page structure of FIG. 6, with m such plane at differing x locations. The (global) bit lines, BL1-m, each run across the top to an associated sense amp SA1-m. The word lines, WL1-n, and source and select lines SSL1-n and DSL1-n, then run in x direction, with the NAND string connected at bottom to a common source line CSL.

FIGS. 9-12 look at a particular monolithic three dimensional (3D) memory array of the NAND type (more specifically of the "BiCS" type), where one or more memory device levels are formed above a single substrate, in more detail. FIG. 9 is an oblique projection of part of such a structure, showing a portion corresponding to two of the page structures in FIG. 5, where, depending on the embodiment, each of these could correspond to a separate block or be different "fingers" of the same block. Here, instead to the NAND strings lying in a common y-z plane, they are squashed together in the y direction, so that the NAND strings are somewhat staggered in the x direction. On the top, the NAND strings are connected along global bit lines (BL) spanning multiple such sub-divisions of the array that run in the x direction. Here, global common source lines (SL) also run across multiple such structures in the x direction and are connect to the sources at the bottoms of the NAND string, which are connected by a local interconnect (LI) that serves as the local common source line of the individual finger. Depending on the embodiment, the global source lines can span the whole, or just a portion, of the array structure. Rather than use the local interconnect (LI), variations can include the NAND string being formed in a U type structure, where part of the string itself runs back up.

To the right of FIG. 9 is a representation of the elements of one of the vertical NAND strings from the structure to the left. Multiple memory cells are connected through a drain select gate SGD to the associated bit line BL at the top and connected through the associated source select gate SDS to the associated local source line LI to a global source line SL. It is often useful to have a select gate with a greater length than that of memory cells, where this can alternately be achieved by having several select gates in series (as described in U.S. Pat. No. 8,933,516), making for more uniform processing of layers. Additionally, the select gates are programmable to have their threshold levels adjusted. This exemplary embodiment also includes several dummy cells along dummy word lines at the ends that are not used to store user data, as their proximity to the select gates makes them more prone to disturbs. These dummy word lines are typically not part of the accessible address space as seen from outside of the memory.

FIG. 10 shows a top view of the structure for two blocks in the exemplary embodiment. Two blocks (BLK0 above, BLK1 below) are shown, each having four fingers that run left to right. The word lines and select gate lines of each

level also run left to right, with the word lines of the different fingers of the same block being commonly connected at a "terrace" and then on to receive their various voltage level through the word line select gates at WLTr. The word lines of a given layer in a block can also be commonly connected on the far side from the terrace. The selected gate lines can be individual for each level, rather common, allowing the fingers to be individually selected. The bit lines are shown running up and down the page and connect on to the sense amp circuits, where, depending on the embodiment, each sense amp can correspond to a single bit line or be multiplexed to several bit lines.

FIG. 11 shows a side view of one block, again with four fingers. In this exemplary embodiment, the select gates SGD and SGS at either end of the NAND strings are formed of four layers, with the word lines WL in-between, all formed over a CPWELL. A given finger is selected by setting its select gates to a level VSG and the word lines are biased according to the operation, such as a read voltage (VCGRV) for the selected word lines and the read-pass voltage (VREAD) for the non-selected word lines. The non-selected fingers can then be cut off by setting their select gates accordingly.

FIG. 12 illustrates some detail of an individual cell. A dielectric core runs in the vertical direction and is surrounded by a channel silicon layer, that is in turn surrounded a tunnel dielectric (TNL) and then the charge trapping dielectric layer (CTL). The gate of the cell is here formed of tungsten with which is surrounded by a metal barrier and is separated from the charge trapping layer by blocking (BLK) oxide and a high K layer.

Defective Word-Lines

The next sections will consider techniques for the identification of defective word-lines. As discussed in the Background, word-line defects can include both leaky word-lines and broken word-lines. Both of these are consider below, with word-line leakage discussed first.

Word-Line Leakage Detection

Under prior art arrangements, the detection of word-line leakage can typically only be done at test time for the memory chip by applying high voltage levels directly to a device's pins and then measuring the current/voltage levels at the pins. This requires the use of a tester device and cannot be done after the memory chip is assembled as part of a device. This means that the word-lines cannot then be checked after device burn-in. The techniques presented here allow for an on-chip means of detecting word-line leakage.

As will be discussed in the following paragraphs, the techniques presented allow for the detection of leakage on a word-line while the word-line has a high voltage applied internally. In an exemplary embodiment, a capacitive voltage divider is used to translate the high voltage drop to low voltage drop that can be compared with a reference voltage to determine the voltage drop due to leakage. The next section will present a related on-chip self-calibration method that can help assure the accuracy of this technique for detecting leakage limit. For both of these processes, the can be under the control of the devices state machine, belonging to a built-in self-test to save on the expensive of an external test device. In this way, the leakage determination can be done in an on-chip, automatic process that does not need complicated test equipment and can be performed in the field after chip is packaged.

First, some discussion of the problem involved here is probably useful. There is an ongoing effect to reduce memory devices to ever smaller scales. As the technology scales down to 20 nm and 10 nm memory cells, for example,

the distance between the word-lines are consequently 20 nm or 10 nm. Tolerances become more critical and the device is more prone to defects that can cause word-lines leak to the substrate or short to adjacent word lines. It has been found that leakage correlates with dies that fail cycling due to grown defects and that detectable leakage seems to precede actual program status failure.

Previous methods for detection of word-line leakage would force a high voltage on the word-line and measure current leakage from a test pin pad. Since the leakage test requires a very accurate current source, this test mode can only be done by a conventional tester. As manufactures would like to migrate most of the test operations onto an inexpensive tester, a new test flow would be useful to be able to implement on-chip means of detecting word-line leakage. This section presents a way to enable the word-line leakage test automatically and internal to flash memory, and in a way that can be done with various voltage biases and multiple stress topologies. The method can also be done in the field after chip being packaged and further allow to system detect different leakage levels.

For a typical device, the word-line leakage could be on the order 100 nA at high voltage stress such as 10 to 20 Volts. The difficulty of detecting such a small current at high voltage is due to the current NAND architecture. This can be illustrated with FIG. 13. The planes of a memory circuit can have on the order of several thousand blocks, one of which is shown at 610 and each block may have several dozen word-lines, three of which are explicitly shown as $WLn-1$ 615, WLn 613, and $WLn+1$ 611. The high voltage is normally applied on the selected word-line, such as WLn 613 during program and read operations. The NAND architecture also has the least area penalty of the word line voltage drivers. The driver is typically connected to the word lines from one end of the word line array. If the architecture allow the connection to word lines from both ends, word line leakage or breakage can be detected by sending a known current from one end and detect the same current from the other end.

The high voltage VPGM is generated by a pump (discussed below with respect to FIG. 14A) and supplied to the first decoding CGN block 601, represented here as a switch. CGN block 601 is a block to supplied the various (typically 3 to 5 different kinds) of voltages according to the mode of operations for each global control gate (CG) lines. Three of the CG lines (621, 623, 625) are shown explicitly, corresponding to the shown word-lines. The CG lines (as many as the number of word-lines in each block) will rout to the row (block) decoder of the memory array. As indicated by the ellipses, the CG lines run to the other blocks of the array in addition to the only shown block of 610, so that these CG lines usually route with the top metal layer and run through all the row decoders of all planes. In one embodiment, each block is decoded with a local pump. When the block is selected, a logic signal will enable the local pump to apply a high passing voltage transferG on the gates of the passing transistors (here represented by 631, 633, and 635 for the three shown word-lines) in the row decoder. The high voltage on the corresponding global CG will be transferred to the word-line of the selected block. Here, only the word-line WLn 613 is shown connected to receive VPGM, with the two adjoining word-lines (611, 615) taken to ground (or more generally the low voltage level), corresponding to the word-line to word-line leakage test pattern discussed below.

During the word-line leakage test, the word-lines can have different bias topology according to the defects to be

detected. In the case of detecting word-line to substrate short, all the word-lines can be biased to high voltage of same levels, with the substrate at ground. In the case of detecting word-line to neighbor word-line shorts, the word-lines in the block will be biased alternatively at high voltage (VPGM) and 0 volts, as shown in FIG. 13. The worst parasitic capacitance will be from the latter case.

FIG. 13 also shows some exemplary, estimated values for the parasitic capacitances involved. From the high voltage pump to the CGN (high voltage to multiplexing block) in a 64 word-line architecture the contribution is roughly 5 pF. Inside the CGN block, the loading will be 4 pF. Each global top metal routing from CGN block to the row decoder at the edge of the memory array is 4 pF. The junction capacitance of one plane is 1 pF. Each local word-line has 2 pF.

In the alternative bias configuration, with a total of 64 word lines, of which 32 word lines are biased to a high voltage while the other 32 word lines are biased to 0V, such as shown in FIG. 13, the total word-line capacitance is $2 \times 32 = 64$ pF. The total global CG line will be $5 \times 32 = 160$ pF. To detect the leakage on the high voltage supply node VPGM, then the total capacitance will be $64 + 160 + 4 + 5 = 233$ pF.

Were the system to use 100 nA of leakage to discharge the large capacitance of 233 pF and let the high voltage to drop 1 volt, this will need a wait of 2.3 ms. After detecting the leakage on even word-line, the odd word-line will be tested with another 2.3 ms. The total leakage test time is around 5 ms.

To reduce the detection time, the voltage drop required for the detection can be reduced to 100 mV, with the corresponding detection time reduced to around 500 us. This can be used for in-field detection operations. In one set of embodiments, this could be executed before each erase operation. For example, the detection can either be included as part of the erase operation sequence or can be done before the erase in response to an instruction issued by the controller. If a block fails, the controller can then remove it from the pool of usable blocks.

The discharge and testing time will depend on the parasitic capacitance of the CG routing. Because of this, one set of embodiments has an on-chip calibration mechanism built in to memory chip so that the precise leakage criteria can be used for detection and the test time can be automatically adjusted according to the chip architecture, word-line voltage stress topology, number of planes, and any other contributing factors. This calibration system is discussed further in the next section.

A normal high voltage pump is normally regulated by a resistor divider, such as shown in FIG. 14A. The high voltage VPGM will be divided by the resistors 645 and 647, connected to ground (or more generally the low voltage level) through the switch SW1 649, and the compare point voltage for the amp 643 will be voltage reference v_{ref} of usually around 1.2 volts. The resistor chain normally will have a leakage current of 10 uA level. The differential amplifier or comparator 643 will be used to output a digital voltage flag-pump which will be used to control the pump clock. When the pump is pumped to the target level, the flag pump will be low to turn off the pump clock. When the high voltage is dropped below certain level, the flag pump signal will go high to enable the pump clock and turn on the pump to supply high voltage.

A detection principle similar to FIG. 13 can be used to detect the voltage change on the large parasitic high voltage node. Since the leakage is in the order of 100 nA, a new way to divide the high voltage to low voltage has to be used. A

comparator is normally built with a low voltage supply for saving I_{cc} current. A capacitive divider has the advantage of no leakage current.

The difficulty with a capacitive voltage divider is that the initial voltage at the detecting point has to be accurately set. As shown in FIG. 14B, a new set of differential amplifiers or comparators **653** is added for the word-line leakage detection on top of that of regulator **643**. The comparison voltage v_{ref1} can be set by a digital to analog converter voltage circuit **651**, whose input can be set according to the device. (In an alternate embodiment, this could also be set as part of the calibration process.) A switch transistor SW2 **659** will be used to initialize the compare nodes at the same voltage level of the regulating level. The capacitors C1 **655** and C2 **657** are the capacitive voltage divider. A ratio is 1:1 can be used. The detection point voltage V_{mid} will have a delta of

$$\Delta V_{mid} = \Delta V_{output} \left(\frac{C_1}{C_1 + C_2} \right)$$

where ΔV_{output} is the high voltage drop due to leakage.

To be able to detect the high voltage change of 100 mV, if the $C1=C2$, then a 50 mV change will be shown at the comparator point. The reference voltage for the comparator will be moved down by 50 mV. If the comparator also has accuracy problems, then the minimum detectable voltage drop will be limited by the comparator. The on-chip calibration can also correct some of the offset and error of the comparator.

The word-line leakage detection is a 3 step detection process, as shown in FIG. 15 where the level on the word-line is shown at **705**. In a pre-charge phase, the word-lines are pre-charged to the high voltage level where the pump is on with regulator setting to targeted level $SW1=v_{dd}$. Enough time should be used to charge the whole word-line. The far side of word-line which located far from the word-line driver side may take a longer time to charge (as shown as the dotted line **707**). The high voltage can also be pumped in two stages: first pumped to an intermediate voltage with another stronger pump, then use the high voltage pump to charge the word-line to a higher level. During the pre-charge time, the detection point V_{mid} is also initialized by turning on SW2.

After the word-line is fully charged to the target level, the pump will be turned off (float), along with the resistor regulator ($SW1=0$). The SW2 is also turned off, trapping a voltage on the mid node.

After some discharge time (a timer can be set with a parameter), the voltage drop will be measured by the comparator **653**. The discharge time will depend on the total parasitic capacitance and the targeted detecting leakage current. (For more accurate leakage detection, self-calibration circuits will be introduced in the next section.) The midpoint voltage will be compared with the v_{ref1} to generate the signal Pass or Fail (P/F). The v_{ref1} voltage is generated from an analog voltage generator **651** which can deliver a voltage between 0 to 1.2 V with 50 mV resolution, as an example.

When word-line leakage is detected, the whole block will typically be marked as a bad block which will not be used. Any valid data could be transferred as needed to another block, although, as noted above, in a set of embodiments the leakage detection process is executed as part of an erase

process. In other cases, for example when the memory has a NOR architecture, single defective word-line could be mapped out.

On Chip Self Calibration for Detection Time

The word-line leakage detection time depends on the parasitic capacitance, which can have large variations depending on architecture, voltage bias topology, and the number of planes. It is, consequently, useful to have a method to calibrate the discharge time with a known leakage current. An on-chip self-calibration algorithm is described in this section. A convenient way of accomplishing this, without needing to add extra elements, is to utilize a known current in the regulator to calibrate the detection time.

FIG. 16 shows the same elements as in FIG. 14B, but as shown in FIG. 16, the resistor voltage divider is used to discharge the high voltage during the calibration process, as shown by the current path I_{dis} **673**. These elements may again be implemented as peripheral circuitry on the memory chip and the path tested in the calibration process should match the path actually used for detection of leakage. During on-chip self-calibration, a good block should be used to determine the characteristics of a block without any word-line leakage. The good block may be determined by its program characteristics or from other some other good block check. For example, data corresponding to the highest state can be programmed and read back to see if it is correct. When the calibration is done on a fresh die, word-line leakage will often not have begun to manifest itself and the location of a good block is generally easy. The calibration is similar with the real leakage test and can be performed in 3 stages, as shown in FIG. 17.

A first phase pre-charges the word-lines of the test block to the targeted voltage level pattern by turning on the high voltage pump, the CGN voltage selection circuits and the row decoder for selected block. The high voltage is regulated by the resistor voltage divider and the comparator to enable pump clock. In this step, SW1 and SW2 are both on, as shown respectively at **801** and **803**. The word-lines charge up as shown at **805** and **807**, respectively corresponding to **705** and **707** of FIG. 15.

The discharge phase will be different from the normal word-line leakage test illustrated in FIG. 15. During the discharge phase, the resistor voltage divider will be kept on with $SW1=v_{dd}$. But the pump is disabled and left floating and $SW2=0$ to isolate the mid node from the resistor divider. The high voltage VPGM will be discharged through the resistor chain with a fixed leakage current along the path **673** of a discharge current of I_{dis} on the order of 10 μA .

When the output P/F **809** of Diff Amp **653** flips after comparing with a selected v_{ref1} value, the amp output Pass/Fail will feed back to turn off SW1. A timer can start counting the time from the start of the discharge phase till the comparator flipping of P/F from pass to fail.

Based on detecting leakage-detection criteria and the ratio of this to the resistor leakage, the timer can be multiplied by a factor of 2 (such as 128) to set the timer counter for detecting targeted leakage current. For example, if the resistor leak 10 μA , the timer multiplying 128 will give the detecting current of 78 nA. (Other factors could also be used, but factors of two are readily implemented, as an easy way to multiply by 2 is to perform a shift of binary digits to the higher bits.)

The calibration only needs to be done once for a given voltage topology during die sort test. The timer digits can then be fixed and stored, for example, in a ROM fuse block. During power on read, the timer digits will be read out to registers and controls the word-line leakage test. For a

different stress topology, a new calibration is needed, since the parasitic capacitance is changed. After each calibration, a corresponding timer parameter can be acquired and saved in the ROM flash memory.

The word-line leakage can be used during manufacture test, or for in-field tests once the device is out of factory. The micro-controller would issue the command to do the word-line leakage test in the user application. A convenient time to do the leakage test is before the erase operation, since the program disturb incurred during the leakage test can be eliminated by the subsequent erase operation.

Detection of Broken Word-Lines

This section looks at the detection of broken word-lines. As device size decreases, in addition to the likely increase in leaky word-lines, the occurrence of broken word-lines is also likely to become more common. A broken word-line will have a high resistive connection across the break, because of which the cells on far end of the word-line (on the other side of the break from the word-line driver) will see a voltage drop during both program and verify operations. This will lead to programming pulses having a lower amplitude, so that cells will be programmed less; but as the verify level is also lowered, these under-programmed cells may still verify. As a result, the threshold voltage distribution for the broken word-line will show two humps, one corresponding to cells one side of the break and the other corresponding to cells on the other side of the break. The method described in this section can be used to identify the broken word-line failure and recover the data of the broken word-line

There are various ways by which the broken word-line failure could be detected. One approach is to use a smart verify scheme. In this arrangement, the program voltage level is recorded when a certain number of bits pass the lower page program operation on each word-line. This recorded program voltage level is then used as a starting program voltage for the upper page of the same word-line. With this scheme, the number of program loops for each word-line is largely uniform, hence any variation in the total program loop number may be used as an indication of a broken word-line. However, as the program loop number in a broken word-line may not be significantly higher than typical, using the total program loop count to judge this failure could result in false alarms

Another approach to detect this sort of failure is the "forbidden zone" read, where a read is performed to determine whether any cells have a threshold voltages in the region between the ranges allotted to data states. In this kind of scheme, after the program operation completes, a particular state can be sensed at two different levels and the results of the two sensing operations can be compared with each other. A scan operation can then be done to check then number of bits between the gaps of two reads which were sensed as non-conducting in one sensing operation, but conducting in the other sensing operation. This solution comes with performance penalty as every single program operation would be followed by two read operations and a scan operation

Yet another method of identifying broken word-lines is to screen out the failure during die-sort. In this method, a whole block is programmed and then read back. (For example, when data is stored in a multi-page format, the lower page of each word-line can be programmed and read twice.) One read is done with a normal read point and another with a raised read point, similar to a forbidden zone read described in the last paragraph. The results of the two sensing operations are then compared using a test-mode command sequence. However, this will only pick up the word-line

breakage that manifests itself at test time, when the symptoms often do not show up until the device has operated over some time. Also, when the word-line already exhibits breakage, it may not demonstrate this on every program cycle and, consequently, may be missed in a single test operation

Considering the problem further, the symptom of broken word-line failure is a distribution with two humps. FIG. 18 shows the threshold distribution of a block of a memory word-line by word-line, for the a 64 word-line example. The distributions for three states are shown at 901, 903, and 905. As shown, these form three well defined and separated humps, where the highest two states, for example, are separated by the region between 923 and 925. For a broken word-line, however, those cells on the far side of the break from the word-line driver will be shifter to lower threshold values, as shown at 911, 913, and 915.

The reason behind a double hump distribution is that the part of word-line at far end of the word-line driver will show voltage drop. As a result, the cells that are located at the far end of the word-line will program slower and pass verify at a lower voltage. Since the failure will not cause a program status failure, it may not be detectable for a typical program failure mechanism. Programming a broken word-line will show some program loop variation, but word-line-word-line and block-block variation make it difficult to judge the failure based on the program loop count, as can be illustrated with respect to FIG. 19. FIG. 19 shows the number of pulse-verify iterations, or loop count, for each word-line to program, in this example, lower page into a 64 word-line block. As shown there, the loop count fluctuates over the different word-lines by several counts. These variations can reflect fluctuations due to the design particulars, such as whether it is an edge word-line or a central word-line, or how many erase-program cycle the word-line has experienced, as well as process variations. In the case of WL50, the loop count is noticeable higher than the other fluctuations, indicating what may likely be a broken word-line, although further tests would be used to confirm whether it is actually broken or this is just a false alarm.

The techniques presented here make it possible to detect broken word-line failure by comparing the program loop count for the cells located on two different sides of the fault. The cells along word-line are programmed and it determined how it takes the cells of different groups or subsets of these cells to verify as programmed to target state, such as writing all the cells to have a programmed lower page. A group with cells on the far side of a break from the word-line driver will take longer to program than a group that has all of its cells between the driven and the break. As memory cells are typically programmed using an alternating pulse-verify algorithm, this can be done by keep track of the number of pulses, or loop count, needed by the different groups or just the difference in the number required. The programming can be done for all of the cells along word-line or some portion of them, such as for system that program the odd bit lines and even bit lines separately. In the exemplary embodiments, the subsets of cells that have their loop counts compared are the contiguous subset of cells of the segment of one end of the word-line and the segment at the other end of the word-line. More generally other subsets of the cells could be used, but by looking at segments from the two ends of the word-line any break should be caught without having to do multiple comparisons of groups' loop counts; and looking at segments of the word-line is generally more readily implementable in the exemplary architecture than if the groups are formed from non-contiguous subsets of the cells, overlapping subsets, or some combination of these. To

be able to compare the loop counts meaningfully for the different segments, their cell should be programmed with the random data, for example, in a multi-page format. The loop count comparison between two ends of the word-line will eliminate the word-line to word-line or block to block variations. The cells on the same word line will follow similar programming characteristics.

Memory devices often already include a scan to check for failed memory bits when programming. The exemplary embodiment incorporates the broken word-line detection into such a routine, which can have several advantages. One is that such scans may already keep track of the loop count for the memory cells or segments as part of their algorithms. Also, as allows the broken word-line check to be performed many times after the device has been in operation, it can pick up breakages that only manifest themselves after device test or that are not detectable at every test.

In an exemplary algorithm, the broken word-line detection is incorporated into a failed bit detection that is done during the last few program loops and which counts the failed bits segment by segment, the word-lines being subdivided into multiple segments. In the exemplary memory embodiment presented above, each the segments can be taken to correspond to one or several adjacent ones of the read/write stacks as shown in FIG. 7. While this scan is ongoing, the scan result of first physical segment and last physical segment on the ends of the world-line can be monitored. When the failed bit count for either one of these two segments end goes below a fixed (in this example) criterion, a signal is latched high to mark the passing of the one segment.

An up-counter can then be triggered when the first of these segments passes the scan. The counter is then stopped when the slower of the two segments passes scan operation. At the end of program routine, the output of the up-counter is compared to the fixed criterion. If the count is higher than the criterion, a signal can be latched high to indicate that a broken word-line has been detected. The up-counter can be implemented on the state machine (112 FIG. 8). As the up-counter can simply count the program look stating when the one segment passes the write criteria, the on-chip state machine will typically be able to keep count of the program loops, so this adds an additional count for it to maintain.

If a broken word-line is detected, its program status should be set to fail and the corresponding cached data should be terminated. The controller can then toggle out the next page of data that if it has been already loaded in the data latches. The next page data can also be programmed to a different location instead of toggling the data out to controller. The data of the failed data page and any corresponding lower pages can then be recovered by issuing a command sequence that will trigger read operation with shifted read voltage levels.

The process can be illustrated by the diagram of FIG. 20 that shows the waveforms for some of the signals involved in this scheme. In this diagram, OPC is the program loop count, corresponding the iteration in the pulse-verify sequence. OPC_DIFF is the up-counter for counting the program loop difference. SEG1_COMP is the latched signal to indicate the passing point of first of segments. LASTSEG_COM is the latched signal to indicate the passing point of the last segment. FIG. 20 picks up the program process after n-1 loops have been completed at time t_0 .

Initially, SEG1_COMP, LASTSEG_COM, and the BROKEN_WL signals are all low and the up-counter is initialized to 0. At t_1 , corresponding loop count n, a first one of the end segments (here taken as the first segment) reaches its

passing point and SEG1_COMP goes high and the up-counter starts, as shown as OPC_DIFF. OPC_DIFF continues to increment up with the loop count until the other of the end segments (here the last segment) passes at t_2 , corresponding to loop count n+3. The signal BROKEN_WL then goes high when $OPC_DIFF > F_OPC_DIFF$.

One complexity that can involve in implementing the above described scheme is the case when the architecture use two sided word-line drivers, placing drivers on both sides of the array (such as would be in the row decoders 230A and 230B of FIG. 1). This can be illustrated by FIGS. 21A and 21B. In FIG. 21A the word-line WL 901A has the driver 905A to the left, closest to the driver. The last segment along the word-line 901A is on the other side of the break 903A from the driver 905A and will consequently see lowered voltage levels and be slower than the first segment. In FIG. 21B the word-line driver 905B is to the right and closest to the last segment close to the last segment along word-line 901B. In this case, the first segment will be on the far side of the break 903B, receive lowered voltages and the first segment will be slower than the last segment. Under such an arrangement, it cannot be assumed that the last segment will pass last, since it may be closest to the driver.

The incorporation of broken word-line detection into a failed bit scan routine is considered further for the case where the memory array includes a number of redundant columns (for use replacement of defective columns), which are placed to the left side of the array so that they all are found in the last segment. One way of implementing a failed bit scan for such a circuit is to scan the segments in the following order: Nth segment (last segment)—1st segment—2nd segment . . . (N-1)st segment. The Nth segment is checked first since this will give an indication of the number of available spare columns to which data from defective columns in other segments can be remapped. In a normal segmented bitscan, which can serve as a basic embodiment upon which this discussion can build, if one segment failed the criteria, the rest of the segment will not be scanned to save time. If segment N fails, the circuit does not proceed to scan the first segment. The process then moves through the other segments, where the criteria for these other segments may consider not only the number of failed bits in this segment but also the number of failed bits in the last segment counting the failures of the replacement columns. In an exemplary embodiment, in case of two sided word-line drivers, the scan circuit should be modified such that it continues to scan the first segment even if the last segment fails. This is shown in FIG. 22. Under this exemplary embodiment, the segmented bitscan is included as part of a normal program algorithm. The broken word-line detection scheme can be integrated into a similar state machine to that for segmented bitscan without the detection. In this arrangement, when the last segment fails, the segmented bitscan is not terminated because the first segment should also be checked to see at which program loop it passed the program. Under one arrangement, if any segment does not finish programming, it is counted as the whole page of data not being finished, and terminates as soon as one segment fails. Similarly, when the broken word line detection is incorporated, the exemplary embodiment will go through the last segment and continue to the first segment regardless of whether the last segment fails or passes.

In addition to the changes just described with respect to FIG. 22, the failed bit scan routine is also modified to include the broken word-line detection process. As noted above, the exemplary embodiment includes redundant columns, so the number of failed bits allowable in the other

sections depends not just on the number of failures there, but also on the number of redundant bits available in the last segment that could be substituted in for failed bits in the first segment. For example, the failed bit count of last segment and first segment are added together and then compared to the criterion in order to determine pass/fail status for first segment. In the exemplary embodiment that incorporates broken word-line detection, the flow will be modified such that the failed bit count for failed segment can be compared to the failed bit criterion in order to determine pass/fail for first segment. FIGS. 23A and 23B show the comparison between a counting scheme that includes neither broken word-line detection nor the process of FIG. 22 (FIG. 23A) and the exemplary embodiment that includes both (FIG. 23B).

The first of these is schematically illustrated in FIG. 23A, which starts at 1001 with a scan of the last segment, including the redundant columns (ColRD), which is then compared against its criteria at 1003 to determine if the last segment has failed. In this embodiment, the process continues (pass or fail) on to the first segment scan at 1005. The criteria used at 1007 for the first segment is compared not just to the scan result for the first segment itself, but also takes into account the number of redundant columns (ColRD) available. If the 1st segment test at 1007 is passed, the flow similarly continues on to the second segment at 1009 and 1011, and so on through the other segments.

In order for the scheme to work correctly in case of two sided word-line drivers, the scan circuit will need to be modified such that it continues to scan the first segment even if the last segment fails. The diagram of FIG. 23B shows a scan algorithm to account for this and that includes the broken word-line check. As before, the scan of the last segment 1051 is compared against the corresponding criteria at 1053. In this embodiment, the process will again continue on the scan of the first segment, 1055, regardless of whether or not the last segments passes or fails, going from 1053 to 1055 if 1053 fails. If 1053 passes, the flow will now go to 1059 as well as 1055. It should be noted that a broken word-line does not necessarily fail to program. When the segment is far from the word-line driver, it will be slower to program, but not necessarily impossible. Hence, it may eventually pass, but it is needed to determine the programming speed at both ends of the word-line, which may differ significantly, in order confirm that a word-line is actually broken.

When the last segment passes, it will trigger the OPC_DIFF block, as will the first segment from 1057, with the first of these to pass starting the counting and the last to pass stopping it in order to count the difference. At 1057 it is judged whether the first segment itself, without the inclusion of redundant columns, passes or fails. As noted, the determination of word-line breakage at 1059 will be based difference from the first segment (alone, without redundant column considerations) and last segment loop counts. 1061 is the bitscan for program status as before, where columns of the first segment may have defective columns replaced by redundant columns (from the last segment). Because of this, both 1057 and 1061 are included in the flow. The process then continues on to the second segment at 1063, 1065 and other segments as before.

By introducing this scheme, the number of defective devices due to broken word-line failures can be reduced without performance penalty. Further, as this is included as part of the programming routine, it is able to pick up breaks that only manifest themselves after a device is shipped. This allows it to be a more efficient and accurate method of

broken word-line detection compared to the other methods due to the fact that it is in-field detection. It can reduce the program loop count variation due to word-line-word-line, block-block and chip-chip variations with no performance penalty and avoids time-consuming die-sort screens.

Determination of Word-Line Leakage by Current Comparison

This section returns to the consideration of word-line leakage and considers some additional techniques for its detection. As before, the techniques can be used to detect word-line leakage to the substrate or to neighboring word-lines. The techniques discussed in the following can be particularly useful for distinguishing the presence of leakage current against the background noise current of a device. Even when no word-lines are selected, there will be some junction leakage current on the path by which the word-lines receive their voltage as it is delivered to through junctions connected to supply the control gate voltages. For example, referring back to FIG. 13, even when the word-line select gates 631, 633, 635 are turned off, there will be some leakage. This background leakage noise will vary with process and temperature variations, and can range over a rather large difference of magnitude. To remove this background current noise, the techniques of this section compare the current drawn by a plane of the memory when no word-lines are selected to the current drawn when a set of word-line are selected. This can be done by using two different planes or by the same plane, where one of the values (such as the reference value with no word-lines selected) is measured and recorded and then compared to the other value. As to when the testing process is performed and the patterns of word-lines selected for leakage testing, these can be the same as discussed above with the other embodiments on detection of word-lines leakage.

The concept can be illustrated with respect to FIG. 24 for the case where two different arrays are used, one unselected and one with an erase block selected for testing, and the two currents are generated at the same time and compared directly. A voltage level, in this example 20V, is generated in a supply VSUP 2021 and supplied through respective resistances R 2023, 2025 to the word-line decoding circuitry of a pair of planes (semi-autonomous memory arrays) Plane 0 2001 and Plane 1 2011, each taken to be of the same design of 2K erase blocks and having respective word-line decoding circuitry, including the word-line selection switches, XDEC of 2003 and 2013. In Plane 0 2001, Block 0 is selected for leakage testing. To do this, the selection circuitry applies a voltage pattern to Block 0's word-lines; for example, a stripe pattern could be applied with the high voltage from line 2005 on ever other word-line and the non-selected word-lines left to float or taken to ground by line 2007. This will detect leakage between the word-lines and also between the (high) word-lines and the substrate. The word-lines in the unselected blocks of Plane 0 2001, and all of the blocks in Plane 1 2003, are then left to float with their word-line select switches turned off. Even though Plane 1 2011 is non-selected, all of the same voltages are supplied along lines 2015 and 2017 to Plane 1's XDEC circuit 2013.

Even though no word-lines are selected in Plane 1 2011, it will draw a certain amount of current $(I_1 = I_{junction})$ due to junction leakage that will serve as a reference value. Plane 0 2001 will draw both junction leakage current and any word-line current I_{leak} . By looking at the voltage difference between node N_0 and node N_1 , the current leakage can be isolated. If the voltage difference, $\Delta V = (V_1 - V_2) = I_1 R - I_2 R = I_{leak} R$, as compared in COMP 2027 exceeds a threshold, the Detect signal is asserted to indicate that the

selected Block 0 has leaky word-lines. In response, the bad block can be mapped out or other corrective actions taken.

Consequently, by using a reference plane and current sensing, the word-line leakage can be detected. Any background noise (junction leakage) will be cancelled through the comparison, since both sides see the same amount of junction area. There is then no reference noise due to differential sensing. Also, the sensing speed is improved since it uses current sensing; and, much as described further for the embodiment presented below, additional reference current can be injected in reference path for margin test.

The arrangement of FIG. 24 requires a device with at least two planes. To be accurate, it also needs that the planes are well-matched: that the reference and selected planes and word-lines have good matching in loading; that the background junction leakage average of the 2K blocks should be at the mean of the distribution; the leakage current on the selected and reference word-lines should match; that the actual leakage criteria is measurable over the difference background leakage; and that the device and resistors are well matched. Also, as the current being drawn through the resistance 2023 is increased by higher I_{leak} values, this can affect the value of R and result in the $I_{junction}$ component not accurately cancelling between the planes (although this effect can be reduced by use of current mirrors, much as described below). The next embodiment overcomes or reduces these various complications.

More specifically, in one embodiment word-line to word-line and word-line to substrate leakage can be detected in-field by determination of a reference level, with all word-lines and blocks de-selected, and then applying a stress mode level done on the same plane by applying voltage levels in a stripe mode on a selected set of word-lines, typically taken to be from a single erase block. To facilitate the accuracy of this process, the exemplary embodiment uses a current mirror scheme.

To give an idea of the current levels involved, calculations for a typical device (based on electronic design rules) give values for maximum junction current at high temperatures to be on the order of several micro-amps and at low temperatures to be on the order of a few tens of nano-amps. Thus, the level of background noise from the junction leakage can vary widely depending on conditions. The amount current that a leaky word-line, whether the leakage is to another word-line or to the substrate, be on the order of a hundred nano-amps to tens of micro-amps. As these numbers illustrate, the relative amount of noise (junction leakage) can be high when compared to the signal (word-line leakage), and both values can vary significantly depending of operating conditions. Consequently, to be able detect word-line leakage, it is useful to have a common-mode current to speed up the detection time, particularly in case junction leakage is low.

In the exemplary embodiment, each plane independently uses a current mirror and current sensing to determine the word-line leakage current. To determine leakage, current is sensed two times (a reference current value and word-line leakage current) and the values are stored digitally and then compared at the end of operation. This arrangement helps to reduce the error terms from current mirror, leakage, and op-amp mismatch. The basic operation can be illustrated with respect to FIG. 25.

The current being drawn by the array, where for determining the reference value or for the leakage test, is mirrored and flow down the left side through the transistor 2105. The level MON is at a high voltage and FLG, on the other side of the inverter 2101 is low. The gate of the

transistor is controlled by the 8-bit (in this example) DAC counter 2107 which starts from the high value (FF in hex) and decrements downward. (Alternately, it could start at the low end and increase, but starting high can have benefits in terms of settling times.) The count continues until the level at MON is pulled above a trip point of FLG, at which point the counter value is stored into the latch Register 2103. After doing this once to determine the reference values, the selected testing pattern is then applied and the process repeated, after which the results are compared to determine if the leakage for the selected set of word-lines exceeds the allowed amount. (Alternately, the reference level determination could be second.) If multiple blocks, or differing applied voltage patterns (e.g., switching which word-lines are high and which are low) are to be checked in the same set of test, the reference level need only be done once and used for the various comparisons.

FIG. 26 shows the elements from FIG. 25 along with some of the other elements used in the exemplary embodiment for the leakage determination circuitry. These elements are connected between the charge pump circuitry 2240, which supplies the high voltages used to apply the test voltages, and the decoder circuitry of the memory plane or planes, which applies the voltage to a selected set of word-lines. In the exemplary embodiment, this circuitry is split into a part that is specific to each plane and, for multi-plane devices, a portion that is shared between multiple planes. The example uses a 2-plane device.

The charge pump system UMPUMP 2240 includes the pump 2241 itself that supplies the high voltage used for testing (here a programming voltage VPGM) and also the resistance 2249 and the comparator 2251 used to set and regulate the value of VPGM. The transistors in between will be discussed below. The voltage is then supplied to the leakage determination circuitry 2220 and 2230.

The portion specific to plane 0 is 2220-0 and the portion specific to plane 1 is 2220-1, with the shared portion as 2230. The portion 2220 transfers the voltage from the charge pump system UMPUMP 2240 to the decoding and word-line circuitry VCGSEL 2260-0, here shown only for plane 0. This is supplied as VCGSEL_P0 and the switch of high voltage transistor 2211 is used to by-pass the detection circuitry for normal operations by passing VPGM to the gate of 2211 by closing the circuit through LVSH. Similarly, during normal operations, the high level of LVSH is also applied to the gate of the high voltage switch of transistor 2243 and the pump system UMPUMP 2240 operates in its typical manner by-passing 2245 and 2247. During testing, both of 2211 and 2243 will be off.

During testing, to determine the amount of current being by the plane, the amount of current being drawn needs to be determined using the process described above with respect to FIG. 25. Rather than use the actual current, and thereby dilute but the measuring process, the current is mirrored by the current mirror 2213, here formed by two pairs of high voltage PMOSs. As some voltage is dropped across the path of the mirror 2213 between UMPUMP 2240 and VCGSEL 2260-0, the two high voltage PMOSs 2245 and 2247 are used to replicate threshold voltage drop across the mirror.

The mirrored current is then used to detect the leakage, whether the reference value or the actual leakage test value, as described with respect to FIG. 25. Transistor 2205, comparator 2201 (here just represented as an inverter), counter 2207 and register 2203 of FIG. 26 respectively correspond to the elements 2105, 2101, 2107 and 2103 of FIG. 25. The comparator 2201 is now also explicitly shown to have as input a reference voltage V_{ref} that could be

supplied by, for example, a bandgap circuit. The capacitor 2209 is also added to smooth out the VMON level. In this embodiment, the elements 2205, 2209, and 2201 are specific to block 2220 of each plane. The block 2230, including counter 2207 and the register/comparator 2203, is shared between block. The counter/comparator 2203 will have a register for each block (2 by 8-bits in this example) and one comparator that can be shared by both planes.

Block 2220 also includes Icm 2215 as a common mode current source to set a minimum current flow through the current mirror to meet settling/detection time. The offset detection current source Ioff 2217 is used during the leakage determination process (including determining the reference value) so that a good block is not detected as bad due to noise determination or detection of error. The offset detection current is used to set a threshold to mark bad block for this purpose.

FIG. 27 is a block diagram to schematically illustrate the relationship of the elements of FIG. 26 to the two planes. The planes P0 2270-0 and P1 2270-1 each have their respective word-line decoding circuitry VCGSEL 2260-0 and 2260-1 that includes the word-line select switches (631, 633, 635 of FIG. 13), as well as any other intervening selection circuitry. In addition to selectively applying VPGM to word-lines, this will apply any other appropriate word-line levels for the various memory operations, where these voltages are collectively indicated as Vcg. (The other peripheral circuitry of the memory circuit is again suppressed here to simply the discussion.) The blocks 2220-0, 2220-1, 2230, and the pump UMPUMP 240 are then as discussed with respect to FIG. 26. In normal programming operations, the blocks 2220-0, 2220-1 are basically bypassed and the same basic paths can be maintained, delivering VPGM as needed; during the word-line stress, however, the new features are then used.

FIG. 28 is a timing diagram for one particular implementation. Here the reference value for the array, but the order could be switched. In this first sub-operation, only the load from the word-line decoding and selection circuitry (or XDEC) is driven to determine the reference leakage. First is an initial ramp-up and stabilization time, during which the current mirror circuits (2213, and 2245, 2247) are bypassed. Here the VPGM value is taken as to be around 17V and the duration of this phase could be something like 50 microseconds, to give them concrete values. Next, the level of VPGM is stepped up to compensate for the voltage drop across the current mirror by replicating the threshold voltages along the path. The LVSH switches are disabled on the current mirror circuits are enable. This takes VPGM to something like $17V + 2 V_{tp}$, where V_{tp} is the threshold voltage of the PMOS devices in the path, so that VPGM is $\sim 20.5-21V$. This leave VCGSEL, on the other side of the transistors, back at around the initial VPGM value of $\sim 17-17.5V$. Here, 200 μs are allotted for this sub-phase. After this follows the detection and store data sub-phase. The duration of this part is determined by the step time of the counter's (2207) time step. Once the reference value is set, then VPGM can be taken low and the leakage determination phase can begin.

To detect the word-line leakage, the load will now include a selected set of word line as well as the decoding circuitry. The first two sub-phases are largely the same, except of the change in load. The last sub-phase, of detection and latching the value is much the same, except that it will now also include the comparison of the two results and the determination of whether the selected set of word-lines, typically a block, contains any leakage. If any additional checks are to

be done at this time, such as for instance switch the selected pattern between the even and odd word-lines of a block, they can be executed using the same reference value.

FIG. 29 repeats the waveform for one (it can be either one) of the phases of FIG. 28, but also shows the leakage current from the array superimposed with the stepping current as determined by the counter (2207, FIG. 26 or 2107, FIG. 25), and the FLG signal from the comparator 2201. Once VPGM is take high in the ramp-up and initialization phase, any leakage current begins to be drawn and the VPGM value is then stepped up. For the detection, the stepping current then begins counting. In the exemplary embodiment, the count will start high and then decrement as this will allow better VPGM settling time and better accuracy through the detection range. Once the stepping current falls below the leakage current, FLG goes low and the data value is latched in register. Once both the reference (REF) and leakage detection test (DET) values are latched, then can be compared. If $DET > REF$, the block (or other selected set) is marked as bad, and if $DET < REF$, the block is marked as good.

FIG. 29 illustrates the "normal" case, where the leakage is within the range of the stepping current. The logic may also handle the cases where the leakage exceeds the stepping current range and also when the level of leakage is very small. For the case when the reference leakage is high, the result is marked as good, while for leakage determination test, the block will be marked as bad. The case of the leakage current being less than stepping current for the REF value determination can be avoided as the common mode current, offset current, or both can adjusted to set the REF leakage to lie in the stepping range. For the DET value, if this is below the stepping range, the block (or other selected set of word-lines) is marked as good.

Current Determination Based on Charge Pump Regulation Clock
Charge Pump Based Over-Sampling ADC for Current Detection

This section considers a further technique for determining leakage in a word-line based upon the charge pump system's behavior while driving the word-line under regulation. This technique is more broadly applicable for determining load current or leakage current from other circuit elements under charge pump output bias and, even more generally, for determining the magnitude of current values supplied from the output of charge pump. Relative to the arrangements of the preceding sections, in many applications this charge pump-based approach can have a number of advantages, including speed of operation, reduced susceptibility to noise, and lower power consumption. It can be executed while executing other on-going operation, rather than as a separate process. Further, as it requires little additional circuitry beyond the standard regulatory elements of charge pump system, it is readily executed for devices that already include a charge pump.

FIG. 30 illustrates an underlying basis of the process used in this section. When a charge pump is driving a load in regulation, then $I_{output} = I_{load}$, determining simple relation between pump load (or leakage current) and the pump clock signals used by the pump to maintain regulation: $I_{output}(\text{pump}) = C * V * f$, where C is the pump coupling capacitance per stage; V is the clock amplitude driving the capacitance C; and f is the frequency of pump clock to maintain the output load of the pump I_{load} . Both C and V are typically fixed values for a pump design, with the frequency varying linearly as load changes. In another word, within a set

amount of time T , the number of pump clocks that occur will have linear relationship with t_{load} .

FIG. 30 shows this sort of highly linear relationship for an actual device, with a linear relationship of (100 pulses/10 μ A) within 50 us. This behavior allows for accurately determining even very low current levels based on counting the number of clocks. This technique of pulse counting for charge pump within a fixed duration incorporates oversampling ADC techniques. Rather than directly comparing the load current with reference current by use of an analog comparator, the pulse counting incorporates many counts over the integration time, and the sampling noise (or background noise) is lowered by accumulating and averaging the results over many pulse counts. If the counting was done only a few pulses, the error could be large due to noise. However by counting many pulses, the randomness of noise is being averaging out over the integration period. The noise floor of current sensing error is reduced through this oversampling technique.

As the pump is already driving the circuit element connected as load, the detection can be performed in background while the operation goes on, without need for a dedicated leakage detection operation. This arrangement can significantly improve detection accuracy and speed, as well as reducing design complexity.

The discussion below will focus on the case where the charge pump system is driving a word-line on a flash memory array and is used to determine whether that word-line has any leakage, but can be used more generally. As it is based on the number of clocks in an interval, it can be used for negative voltage charge pumps as well as the more usual positive voltage case. Thus, as well as word-lines or other elements on a non-volatile memory circuit, it could also be used to detect background leakage on DRAM devices, for example.

The general process can be considered further with reference to FIGS. 31 and 32, which illustrate a pump driving a current load I_{load} and a load of twice I_{load} . In FIG. 31 the pump 3001 receives an oscillator signal from the regulation circuitry (not shown) that is based on the output level. The pump 3001 then generates an output current I_{output} that drives the load 3003 at I_{load} . While operating under regulation, the number of clock pumps is counted over a time $T_{duration}$ when a control signal Detection Phase is high. In this example, the number of clocks is 6. FIG. 32 schematically illustrates the same situation, but where the load 3003' now draws twice the current, $2 \times I_{load}$, where now 12 clocks are counted during the interval. This count can then be compared to a reference, such as could come from a calibration process or driving other components, to determine that amount of current and whether there is leakage.

FIG. 33 is a block diagram to illustrate further the circuitry involved for typical implementation. The output V_{out} is fed back to the regulation circuitry 3005, where it is compared to a reference value. Based on the comparison, the signal OSC is then varied to maintain the output in regulation. The OSC signal is also sent to a current detection block 3007 where, when the number of clocks is counted for $T_{duration}$ in response to a control signal Detect. (Here, this is shown as an input to the block 3007, but this could also be determined internally in other embodiments.) The current determination block 3007 then puts out the result I value, which can be presented in different ways according to the embodiment. For instance, if block 3007 is only checking for leakage, the output may just indicate whether or not the count exceeds a reference value. In other cases, the output could be the count, which can then be converted to a current

value elsewhere, or the conversion could also be done in 3007. (More detail on charge pump systems and their regulation can be found in the group of references cited above.)

Consequently, this simple relation between leakage, or more generally load current, and the number of pump clocks allows for accurate current determination. Although higher order corrections could be introduced, the high degree of linearity means this is not needed in most applications. As the number of clocks over the interval allows an accurate determination, this can remove the need to insert any additional circuitry in the current path in order measure current. Just need count and make determination. For the exemplary embodiments most of concern here, such as in memory operations, by accumulating the total number of pump clock during a given detection phase, and comparing this with a criterion, which can be predefined or pre-calibrated, the system determine whether leakage is occurring—or, more generally, the amount of load current being drawn. The decision can easily tell if something, such as leaking word-line, is causing an extra load current for the pump.

Returning back to FIGS. 26 and 27, this means that according to the embodiments of this section the elements of blocks 2220 and 2230 are not needed. The pump element 2240 can then be a standard pump system, but with the addition of the current detection elements based upon the count.

FIG. 34 is an exemplary timing diagram for embodiments of this section and corresponds to FIG. 28 of the previous section. Initially, the pump needs to ramp up to, in this case, the VPGM value of $\sim 17V$. Note that unlike in FIG. 28, the level does not need to be pumped to the higher level, but only the level actually used in the operation. Without the word line load attached, the system start checking background noise due to junction leakage and other current drawn even when the component to be measure is not yet connected as a load. Once under regulation, the system acquires the pump clock counts of N . In this example, the different phases are taken to have a duration of 10 us, but other values can be used, including different values for t different determinations. With the word line connected, once out of the recovery phase the system can start to check for the noise leakage plus any word-line leakage current. In the measurement (here 10 us) window, the system acquires pump clock counts of $N+M$ that can then be compared to a reference value to determine whether the word-line is leaking. For example, the system can determine the word line leakage pulse counts M , subtract, say, two counts, and compare it with a pre-defined criterion and make the judgment on if the word-line is leaking. Note that this process can be done more quickly that that shown in FIG. 28 since it does not require stepping up the VPGM values to the higher level before the detection interval and also the big drop in the middle is removed; and as already noted, this can be done on the fly during a regular operation.

Consequently, in many applications the techniques of this section can have a number of benefits relative to those of the preceding section. For one thing, it has lower susceptibility to noise. As the elements 2220 and 2230 of FIGS. 26 and 27 are no longer needed, noise from elements such as the current mirror 2213 of FIG. 26 is eliminated. Also, as a longer integration time can be used to determine the count in FIG. 34 relative to the detection time of FIG. 28, other noise (such as from word-line to word-line coupling) is smoothed out due to an effective over-sampling technique for a DAC encoding of the load's current.

29

As discussed above, the current from the pump is given by the relation $I_{output}(\text{pump})=C*V*f$, where C is the pump coupling capacitance per stage; V is the clock amplitude driving this capacitance C ; and f is the frequency of pump clock. In the example of $I_{output}(\text{pump})=C*V*f$, where C is the pump coupling capacitance per stage; V is the clock amplitude driving capacitance; and f is the frequency of pump clock for the output load of the pump I_{load} in regulation. To determine the current being drawn by the load, the number of clocks of a time period is counted; for example, in FIG. 31 6 clocks are counted over the interval of $T_{duration}$. As the smallest variation that can be determined is a difference of count, this would mean that the smallest change from this base line calibration value that can only be established $1/6$ th calibration value. This can be made more accurate by designing the pump system to have a high number of clocks during the detection phase by having a lower value of C (the pump coupling capacitance), V (the clock amplitude), or both. For example, designing the pump system to have both C and V reduced by half would increase the number of clocks during the detection phase by a factor of 4, consequently increasing the accuracy by which the load current can be determined. This is a design choice balancing a number of factors, but generally having the system designed so that a higher number of clocks, say 10 or more, during the detection phase can improve the accuracy of the techniques of this section.

The preceding section is developed further in U. S. patent publications 2014/0084936 and, 2014/0085985.

Charge Pump Based Determination with Uniform Step Size

This section considers techniques to further improve the accuracy of the charge pump based current determination technique. More specifically, different current determinations may be performed at different voltage levels. For instance, when testing for word line to word line leakage, a high voltage can be used, as the structures involved are designed to support programming voltages; but other structures, such as in testing for the leakage of a word line to, say, a local interconnect (or LI, such as discussed above with respect to the structures of FIGS. 9-12) may not be designed to support such high voltage differences. Consequently, it is useful to be able to accurately detect the amount of current being drawn for a wide range of applied voltages. As a charge pump will have different levels of efficiency when being operated to supply different output voltages, the accuracy of the current determination (or the time needed to make a sufficiently accurate determination) will vary based on the voltage. This section looks at being able to perform the leakage determination with higher accuracy/performance across a wide range of drive voltages. Although the following discussion is again presented primarily in the context of determining whether a word line is leaky, the techniques can be more generally applied, both to other control or bias lines of a memory array (such as bit lines or select lines), but also to other circuit components on memory chips or other circuits, whether as leakage test or just to more generally determine the current drawn.

The situation can be considered with respect to FIG. 35, which combines elements similar to those of FIGS. 31 and 32. A pump 3501, under regulation generates a V_{out} to drive a load on the array 3505 that draws a current I_{load} . The current out of the pump $I_{output}=C*V_{out}*f_{pump}$, which are respectively the capacitance of the load, the pump's output voltage, and the frequency of the clock CLK. A counter 3503 counts the number ($\#CLK$) of clock during the detection time T_{detect} . The corresponding amount of charge is the

30

number of clock cycles $\#CLK$ times the amount of charge per cycle, which is equal to $I_{load}*T_{detect}$ or $C*V_{out}*(\#CLK)$.

Under this arrangement, the current leakage from the array (or, more generally, the current drawn by the load) is translated to the pump count ($\#CLK$), or the number of on/off cycles of the clock. The count is directly proportional to leakage current, where a longer detection time is realized to achieve a smaller step size, where the step size is the load current divided by the number of cycles during T_{detect} : Step size=leakage current/ $(\#CLK)$. This is illustrated in the wave forms in the lower part of FIG. 35, where WLLD_DET_V is the enable signal for the current detection operation. Over a detection period T_{detect} for a reference load level the number of counts is 6, while for twice this current the count is 12. If the count is taken over $2T_{detect}$, the count for $2\times$ the reference load current will be 24.

FIG. 36A is a schematic representation similar to that of FIG. 35: a pump 3601 under regulation (the regulation circuitry is left out here to simply the figures) drives a word line or other load in array 3605, while the control circuitry and counters 3603 tracks the number of cycles of the clock CLK. Here, the regulated value of V_{out} can be changed from, say, 5V to 18V based on the control input BINVOUT. A charge pump's strength tends to have a large amount of variation depending on the output voltage (V_{out}) level at which it is being regulated, as illustrated with respect to FIG. 36B. The current requirement for the pump is shown as I_{load} , which is level above the $I=0$ line across the different voltage levels. The pump load line represents the drive capability relative to I_{load} across this range. As shown, extra capability (how far the load line extends below the $I=0$ axis) at the low end of the V_{out} range is much greater than at the high end. Because of this, fewer pump cycles will be needed to supply the same I_{load} at a lower V_{out} and the V_{out} waveform will be "spikier" (that is, having higher or longer ripples) at the lower value, showing fewer pumps of greater charge.

This will also affect the count or step size, since for the same I_{load} , the count will be different depending on the regulated output voltage V_{out} : For higher V_{out} , the count is higher due to relatively weaker pump capability (the pump is on more often for the same I_{load}); and for lower V_{out} , the count is less due to stronger pump capability (pump is on less often for the same I_{load}). Consequently, the amount of leakage for a given count varies with the voltage level used for the determination, with lower voltages either having lower resolution for a given detection time or requiring a longer detection time to provide the same level of resolution.

FIG. 37 illustrates a design to isolate the pump strength variation due varying V_{out} and have a uniform step size across the V_{out} range. Rather than have the pump 3701 drive the load at 3705 with a variable V_{out} to detect leakage, the pump is set to generate a single fixed voltage (such as $\sim 18.5V$ in this example) during detection, and regulated at this level, that is used as supply level for a step-down regulator 3711. The counting clock at 3703 is still generated from the pump, but the step-down regulator is used to drive the load at the target stress voltage (such as over the range 5V to 19V in this example), as set by the control signal BINDAC. The switches 3713 and 3715 respectively are a schematic representation of how the step-down regulator 3711 can be connected to use the fixed V_{out} as the supply level to drive the load at levels lower than V_{out} . The step-down regulator can be actively regulated or passively regulated, such as those described in U. S. patent publication 2016-0049206, for example. As the pump is now being operated at the same V_{out} independently of the V_{step} level

31

being applied to the load, the count for a given I_{load} will be consistent regardless of stress voltage applied.

CONCLUSION

The foregoing detailed description has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the above to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. The described embodiments were chosen in order to explain the principles involved and its practical application, to thereby enable others to best utilize the various embodiments and with various modifications as are suited to the particular use contemplated. It is intended that the scope be defined by the claims appended hereto.

It is claimed:

1. A circuit, comprising:
 - a charge pump;
 - regulation circuitry connected to receive an output voltage of the charge pump and regulate the output voltage of the charge pump at a first voltage level by varying a frequency of an oscillator signal supplied to the charge pump;
 - a step down regulator connected to receive a control signal and connectable to receive the output voltage of the charge pump and generate therefrom a first one of a plurality of regulator output voltage levels having a value dependent upon a level of the control signal, the step down regulator further connectable to drive a load with the first one of the regulator output voltage levels; and
 - current detection circuitry connectable to the regulation circuitry to determine a number of cycles of the oscillator supplied to the charge pump during an interval of a first duration in order to maintain the output of the charge pump under regulation at the first voltage level while driving the load at the first one of the regulator output voltage levels and, from the determined number of cycles, determine an amount of current being drawn by the load.
2. The circuit of claim 1, wherein based upon the amount of current being drawn by the load, the current detection circuitry determines whether the load is leaking.
3. The circuit of claim 1, wherein the current detection circuitry determines the amount of current being drawn by the load by comparing the determined number of cycles to a reference value and, based upon the comparison, determining the amount of current being drawn by the load.
4. The circuit of claim 1, wherein the circuit is formed on a memory circuit including an array of memory cells and the load is a control line of the memory array.
5. The circuit of claim 4, wherein the control line is a word line.
6. The circuit of claim 4, wherein the memory circuit is a monolithic three-dimensional semiconductor memory device in which memory cells are arranged in multiple physical levels above a silicon substrate and comprise a charge storage medium.
7. A method, comprising:
 - generating an output voltage by a charge pump;
 - regulating the output voltage at a first voltage level by varying a frequency of an oscillator signal supplied to the charge pump from regulation circuitry connected to receive the output voltage;
 - receiving at a step down regulator a control signal;

32

while generating the output voltage regulated at the first voltage level, receiving at the step down regulator the output voltage, generating therefrom a second voltage level having a value dependent upon a level of the control signal, and driving a load with the second voltage level;

while driving the load with the second voltage level, determining a number of cycles of the oscillator supplied to the charge pump during an interval of a first duration in order to maintain the output of the charge pump regulated at the first voltage level;

comparing the determined number of cycles to a reference value; and

based upon the comparison, determining an amount of current being drawn by the load.

8. The method of claim 7, further comprising:

based upon the amount of current being drawn by the load, determining whether the load is leaking.

9. The method of claim 8, wherein the comparing includes determining whether the number of cycles exceeds a reference value.

10. The method of claim 9, wherein the reference value is determined as part of a calibration process.

11. The method of claim 10, wherein the calibration process is performed as part of a test process.

12. The method of claim 7, wherein the reference value is determined by the number of cycles of the oscillator supplied to the charge pump during an interval of a second duration in order to maintain the output of the charge pump under regulation while driving junction circuitry by which the load is connected to the step down regulator, but not driving the load.

13. The method of claim 7, wherein the charge pump, regulation circuitry and step down regulator are formed on a memory circuit including an array of memory cells and the load is a control line of the memory array.

14. The method of claim 13, wherein the control line is a word line.

15. The method of claim 13, wherein the memory circuit is a monolithic three-dimensional semiconductor memory device in which memory cells are arranged in multiple physical levels above a silicon substrate and comprise a charge storage medium.

16. A memory circuit, comprising:

a memory array;

a charge pump system, including:

a charge pump; and

regulation circuitry connected to receive an output voltage of the charge pump and regulate the output voltage of the charge pump at a first voltage level by varying a frequency of an oscillator signal supplied to the charge pump;

a step down regulator connected to receive a control signal and connectable to receive the output voltage of the charge pump and generate therefrom a regulator output voltage level having a value dependent upon a level of the control signal, and the step down regulator further connectable to drive a bias line of the array with the regulator output voltage level; and

current detection circuitry connectable to the charge pump system to determine a number of cycles of the oscillator supplied to the charge pump during an interval of a first duration in order to maintain the output of the charge pump under regulation at the first voltage level while driving the bias line of the array at the regulator output

voltage level and, from the determined number of cycles, determine an amount of current being drawn by the bias line of the array.

17. The memory circuit of claim **16**, wherein based upon the amount of current being drawn by the bias line, the current detection circuitry determines whether the bias line is leaking. 5

18. The memory circuit of claim **16**, wherein the current detection circuitry determines the amount of current being drawn by the bias line by comparing the determined number of cycles to a reference value and, based upon the comparison, determining the amount of current being drawn by the bias line. 10

19. The memory circuit of claim **18**, wherein the comparing includes determining whether the number of cycles exceeds a reference value. 15

20. The memory circuit of claim **16**, wherein the bias line is a word line.

21. The memory circuit of claim **16**, wherein the memory circuit is a monolithic three-dimensional semiconductor memory device in which memory cells are arranged in multiple physical levels above a silicon substrate and comprise a charge storage medium. 20

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